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THE PENNYLAND PROJECT

Prof. J. Chapman, Dr. R. Lowe
& R. Everett

ERG 053

ETSU-S-1046

Energy Research Group

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This is the final report on the performance of 177 low-energy, houses at Pennyland, Milton Keynes, monitored by the Open University Energy Research Group (ERG), for the Milton Keynes Development Corporation (MKDC), under contract to the Energy Technology Support Unit (ETSU) at Harwell.

The principal authors are J. Chapman, R. Lowe and R. Everett (ERG).

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OTHER REPORTS:-

Linford Low Energy Houses, R.Everett, A.Horton, J.Doggart & J.Willoughby, Energy Research Group, Open University, Jan. 1985. Available as ERG 050/ETSU-S-1025 (Full report) or ERG 051/ETSU-S-1025(s) (Executive Summary).

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Buildability of Highly Insulated Masonry Houses with Enlarged Cavities and Built in Thermal Insulation, B.O.Hall & P.Finch, B.R.E. note N77/81, June 1981, B.R.E., Garston, Watford.

The Rapid Thermal Calibration of Houses, R.Everett, Energy Research Group, Open University, June 1985, ERG 055.

UNITS

The kilowatt-hour has been used as the principal unit of energy in this report, rather than the gigajoule or the therm, since it is probably the most intelligible to the layman. The slightly curious unit of the 'mean watt', ~~since~~ a continuous energy consumption of one watt, has been used in the regressions for ease of computation.

1 Joule	=	1 Watt-second
3600 Joules	=	1 Watt-hour
3.6 Megajoules (MJ)	=	1 Kilowatt-hour (kWh)
1 Gigajoule (GJ)	=	278 kWh.
1 Therm	=	100,000 British Thermal Units (BTU.)
	=	29.3 kWh.
1 MJ	=	10^6 Joules
1 GJ	=	10^9 Joules
1 Terajoule (TJ)	=	10^{12} Joules
1 Petajoule (PJ)	=	10^{15} Joules
1 Million Tons Coal Equivalent (Mtce.)	=	26.4 PJ
1 Mean Watt	=	8.76 kWh/yr
1 kWh/m ²	=	315.4 BTU/ft ²
1 Langley	=	1 cal/cm ² /day
	=	0.0116 kWh/m ² /day

CHAPTER 1

INTRODUCTION

This chapter describes the history of the project, the relation with the companion Linford project and gives a brief description of the other chapters.

1. INTRODUCTION

This Report describes the results of a large scale housing project carried out in Milton Keynes by members of the Open University Energy Research Group between 1976 and 1984. The project was conceived and developed by the Energy Consultative Unit, a joint venture between the Open University and Milton Keynes Development Corporation, and has received financial support from the Dept. Energy and the Dept. Environment as well as from the OU and MKDC. The overall aim of the project was to investigate the potential energy savings that could be achieved through better house insulation and the incorporation of passive solar design features.

The city of Milton Keynes is laid out with a rectangular network of major roads (so called grid roads). Each rectangular element, known as a grid square, is developed separately and given an individual name. The Pennylands estate, consisting of about 420 houses, lies in a small grid square in the northern half of Milton Keynes. The energy experiments have been carried out on a group of 177 houses occupying the northern half of the Estate. The houses were laid out and designed according to an energy brief which emphasised certain passive solar features; namely southerly orientation, minimal overshadowing of south facades, concentration of glazing and living rooms on the south side, high thermal mass and insulation levels. The estate was finally constructed with two standards of insulation with a view to evaluating the resulting differences in energy consumption.

The Pennylands project was conceived in association with another project also mounted in the northern part of Milton Keynes and referred to as the Linford project. The Linford project complements the investigations carried out at Pennylands since it involves a very detailed study of a much smaller number of houses incorporating similar insulation and passive solar features. At the Linford site there are eight identical houses, all larger than the Pennylands houses and insulated to the highest Pennylands standard. One of the eight houses was used by the research team as a test house and gave many detailed results on the thermal performance of this type of building. The other seven houses were sold and occupied normally. All the houses were intensively monitored so that the effects of occupant behaviour could be gauged. In broad concept the Linford project provides results on the detailed thermal performance of low-energy passive solar houses whereas the Pennylands project gives large scale statistical information with which to confirm or qualify these results on a larger scale.

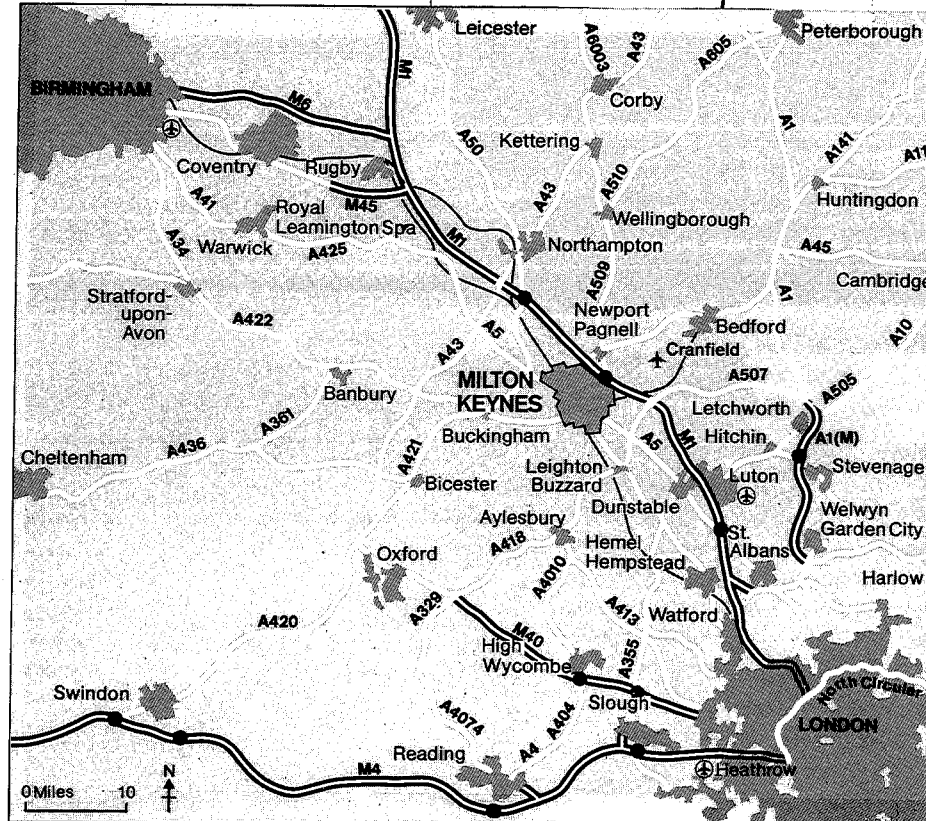


Fig.1.1
Location of Pennyland
Estate

One important characteristic of both these projects is that they were for real housing schemes i.e. they had to meet all the normal criteria for public sector (Pennylands) and private sector (Linford) developments. The constraints imposed by the wide range of non-energy criteria had two broad effects. The first was on the timing of the two projects. Initially it was planned to complete the preliminary analyses of the small scale (Linford) project before finalising the designs of the larger scale project at Pennyland. In this way any obvious lessons from the small scale work could be incorporated into the larger scheme, thereby refining its experimental objectives and ensuring it would not cause serious problems for the residents. This neat timescale, devised in 1976, had to be abandoned and the two projects ended up running in parallel. The fact that both projects came "live" at the same time also imposed severe strains on the technical resources of the research team. The second major effect was that in several cases the experimental design of the Pennyland project was jeopardised. The experiment required that there should be groups of houses that were identical in all respects except those being tested. In this way the differences being tested would show up as differences in the average fuel bills of the different groups. It was necessary to have quite large numbers of houses in each group so as to reduce the differences in fuel use caused by different lifestyles and comfort requirements. As will become clear later in this Report the difficulties in getting large enough groups of identical houses has led to difficulties in obtaining unambiguous results. Nevertheless there have been significant benefits from conducting the large scale trial at Pennylands, not least of which is that the low energy, passive solar concept has been proven in practice. Although the experiment has been made more messy by the incorporation of normal architectural constraints, the basic concept has survived through it all and proved itself to be flexible enough to be incorporated in a significant range of environments.

In order to arrive at firm conclusions from a statistical experiment it is necessary to have a control group. In this case what is required is a group of similarly sized houses, built to normal insulation standards and without any particular emphasis or attention being paid to orientation, overshadowing or other passive solar features. The estate chosen as the control group for the Pennylands project was Neath Hill, a grid square adjacent to both the Pennylands and Linford projects, as illustrated in Figure 1.1. With the control group so close differences in climate are minimised and monitoring convenience increased. The Neath Hill estate was built prior to the Pennylands estate and in fact was built to 1975 Building Regulation standards. The Pennylands estate incorporated the projected 1982 regulation standard and a higher standard of insulation

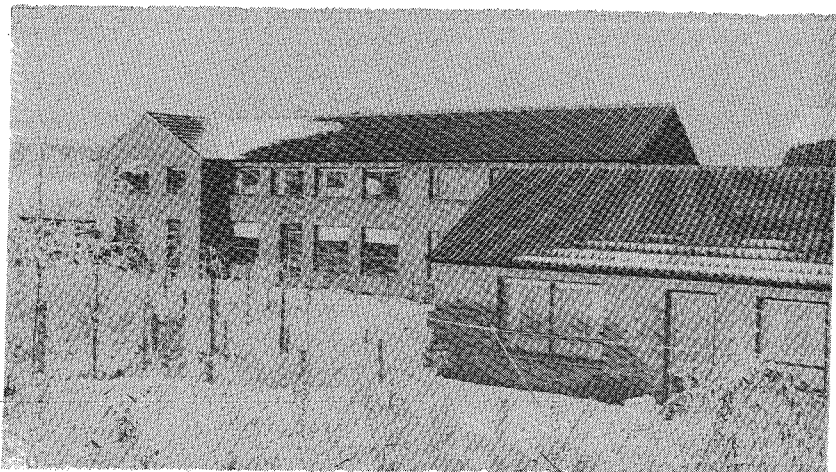


Figure 1.2
South-facing
Pennyland Area 2
houses

Figure 1.3
East-west facing terrace
of Neath Hill houses

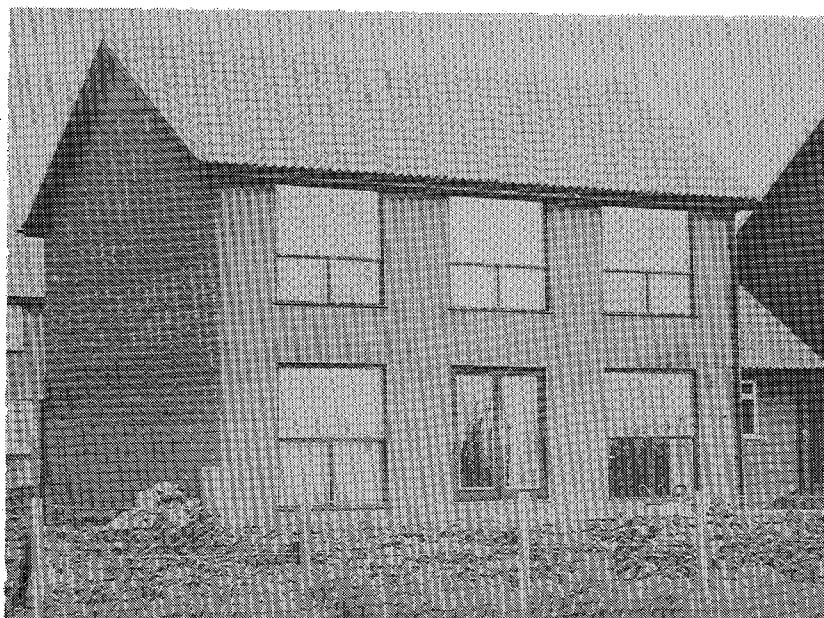
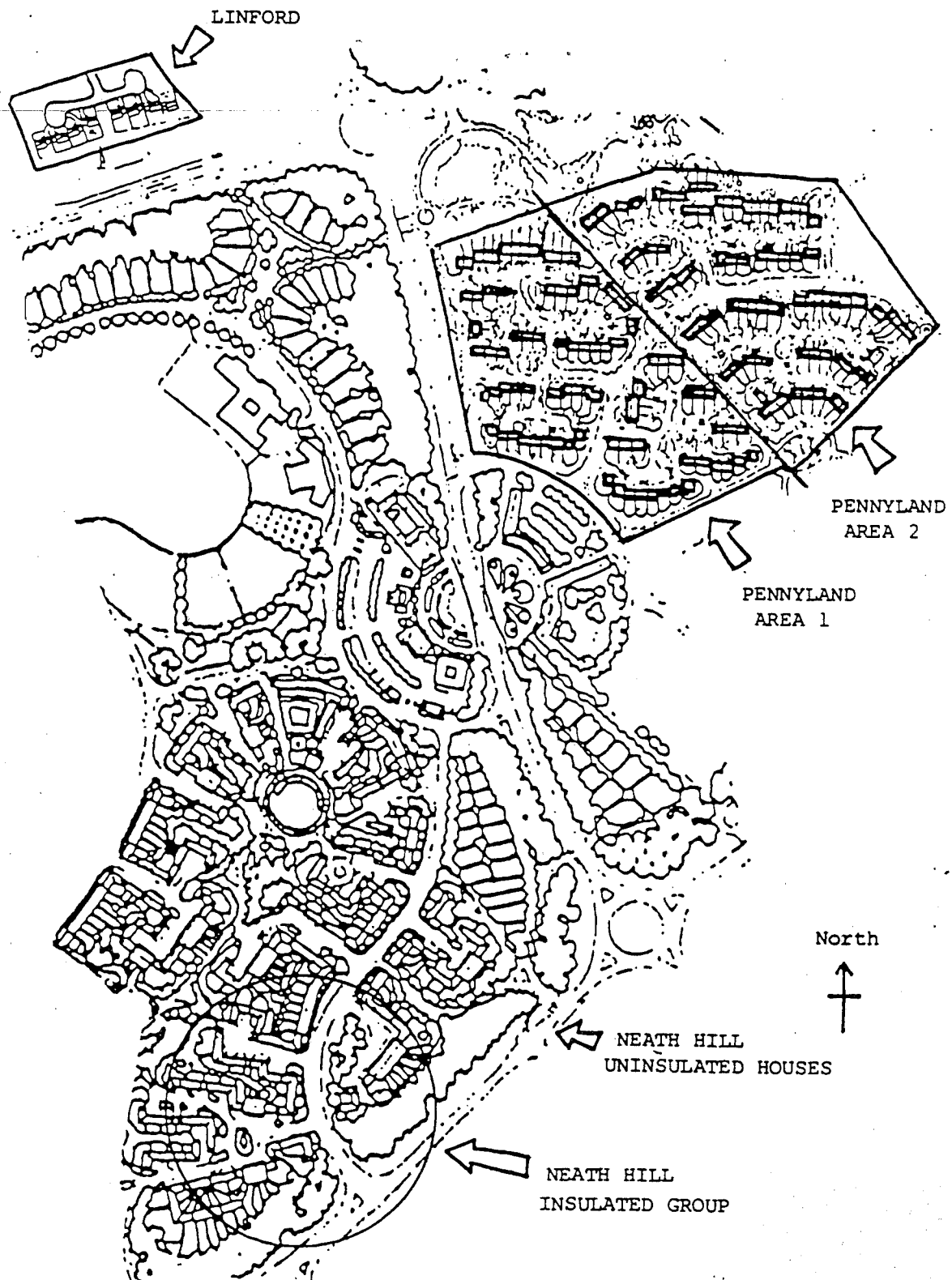


Figure 1.4
Intensively monitored
Linford houses, similar
in design to the
Pennyland Area 2
single aspect houses.

Figure 1.5 LINFORD AND PENNYLAND PROJECT HOUSES



(roughly corresponding to the Danish building regulations BR-77 introduced there in 1979). In order to provide controls for both the insulation and passive solar parts of the Pennylands experiment two control groups were established on the Neath Hill estate. One was "as built" and provided a control for the insulation study; the other was subsequently better insulated, approximately to the standard of the 1982 regulations, and thus provided a control for the passive solar component (since the Neath Hill estate was not laid out with any attention to orientation, overshadowing and so on). In the event detailed comparisons between the Neath Hill control groups and the Pennylands groups showed up other differences, not planned as part of the experiment but nevertheless highly significant.

Figure 1.6 sets out the main chronology of the projects and figure 1.7 shows the relationship between the different insulation standards and passive solar features across the estates. On the Pennylands estate there were two major house types, one of which was fairly normal (referred to as a dual aspect house) but with overshadowing minimised and a southerly orientation, the other having more glazing on the south face and living rooms organised on the south side of the building (this latter type is referred to as the single aspect house type). The Linford houses simply extended this further with a larger south facing glazing area. Had all the experimental conditions been satisfied there would have been six comparisons which could be usefully made, as indicated by the double headed arrows on Figure 1.7. In the event most of the passive solar comparisons were unable to produce statistically significant results.

The monitoring strategies on Linford and Pennylands matched the different aims of the projects. At Linford each house was "wired up" with up to 50 different sensors and the data recorded on data loggers installed in the test house. At Pennylands the main monitoring was by weekly reading of gas and electricity meters. In order to be able to reduce the variance of the observed energy consumptions groups of houses on Pennylands were more intensively monitored with an extra gas meter, one or two heat meters and temperature measurements. All these additional measurements were fed to simple readouts in the meter cupboard so that the data could be collected as part of the weekly round. The sheer volume of data collected on both projects is enormous and there was a major effort required to set up data handling and analysis systems before any results could be deduced.

The main energy consumption results of the Pennyland study are summarised in Table 1 below and shown as histograms in figure 1.8.

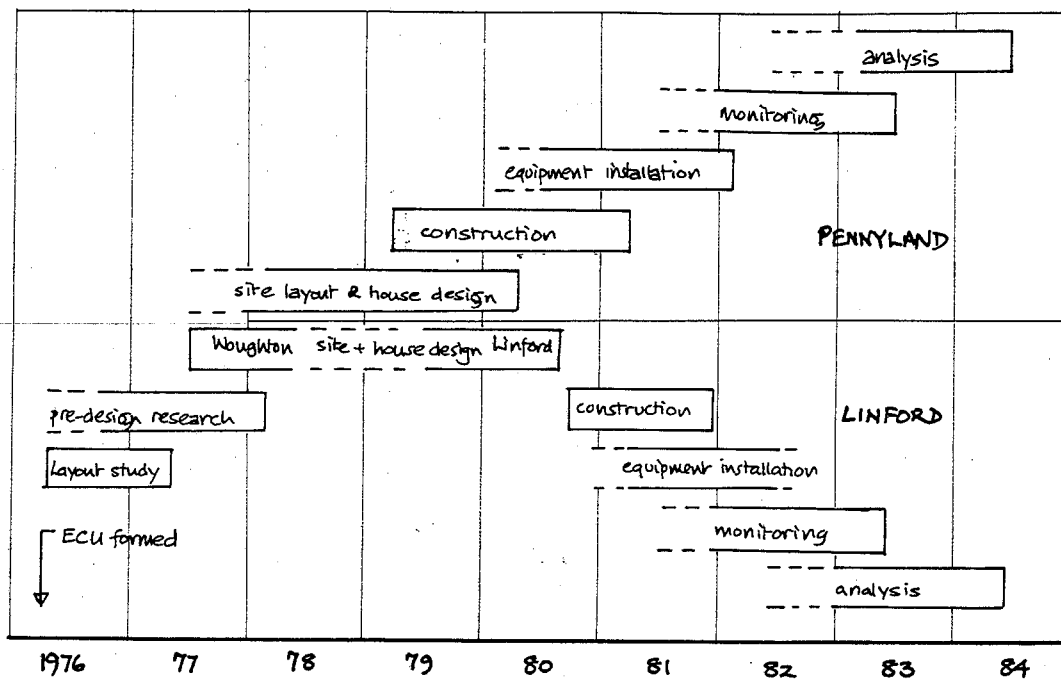


Figure 1.6 The chronology of the Linford and Pennyland projects

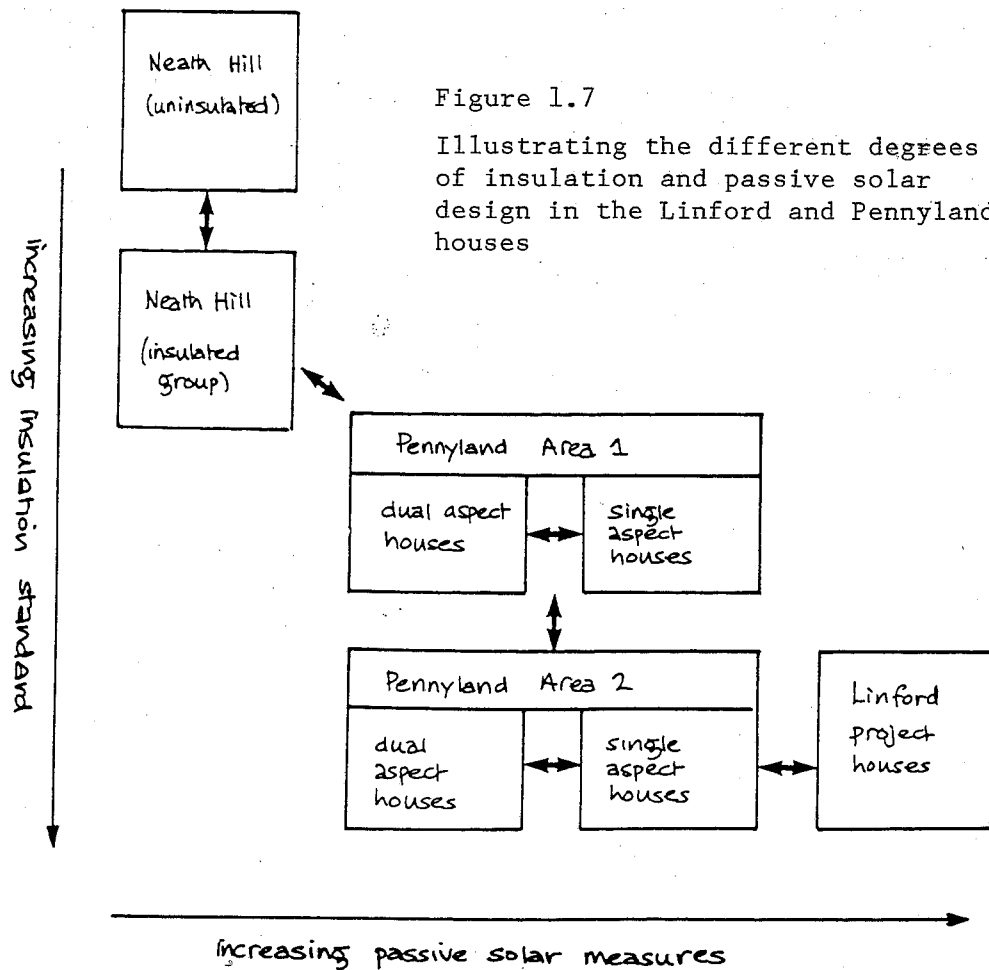


Figure 1.7

Illustrating the different degrees of insulation and passive solar design in the Linford and Pennyland houses

TABLE 1. Summary of gas average consumption and space-heating requirements for Pennylands and Neath Hill. (kWh/year)

	Annual gas consumption	Gas used for space heating	Space heating useful energy
Neath Hill			
uninsulated	23400	(15760)	(9360)
insulated	22480	14840	8680
Pennylands			
area 1	14010	9500	6360
area 2	11530	7700	4830

There are several striking features of these results. First, as expected, insulation clearly saves energy. The saving by insulating Neath Hill (from 1976 regs. to 1982 regs.) represents a saving of about 4%, though as can be seen from figure 1.8, this is subject to much statistical uncertainty. Similarly the saving from the additional insulation on Pennylands area 2 as compared to area 1 represents a saving of 18%. However the biggest difference exists between the insulated Neath Hill houses and the Pennylands area 1 houses, this difference is equivalent to a saving of 38% of the gas consumption of a Neath Hill house. Investigations of this difference point to two main factors.

First the two estates use different boilers, and these have been found to have significantly different efficiencies. The low thermal capacity boilers installed on Pennylands save about 3000 kWh/yr when compared to the conventional boilers used on Neath Hill.

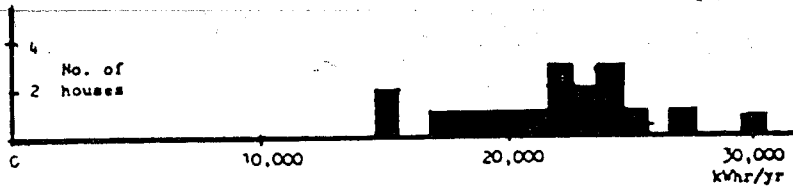
The second difference is in air infiltration in the two sets of houses, and it is this factor which largely accounts for the difference in useful energy consumption. Pressure test results show that the Pennylands houses are significantly tighter than those on Neath Hill; it is thought that this is due to the cast concrete form of construction, the better sealing around windows and the design of door lobbies in the Pennylands houses.

Overall the improved standard of insulation, the better boiler efficiencies and the reduced infiltration rates have lead to an overall reduction in gas use of 51%. As detailed in the main body of the report most of these savings have been achieved at little or no extra cost, thus making the improved house designs extremely cost effective.

Partly because of the changes in house design and layout in the late stages of construction, partly because of the problems of monitoring and

TOTAL ANNUAL GAS CONSUMPTIONS

October 1981 - September 1982



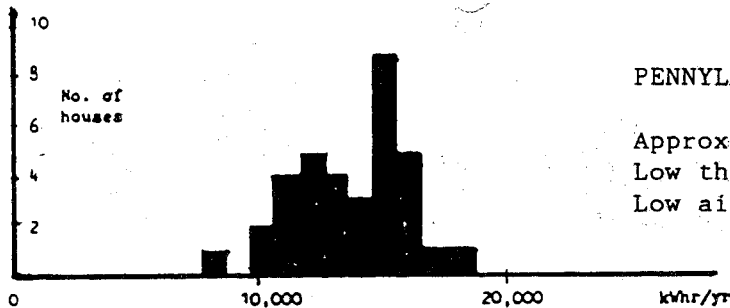
NEATH HILL UNINSULATED GROUP

1976 Regs. insulation standard
Conventional gas boiler
Normal air change rate



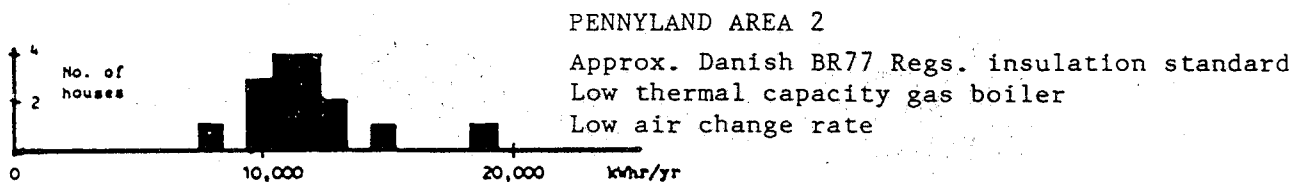
NEATH HILL INSULATED GROUP

As above but with 50mm cavity
wall insulation



PENNYLAND AREA 1

Approx. 1982 Regs. insulation standard
Low thermal capacity gas boiler
Low air change rate



PENNYLAND AREA 2

Approx. Danish BR77 Regs. insulation standard
Low thermal capacity gas boiler
Low air change rate

Figure 1.8 Annual gas consumptions for the four main insulation groups

having an inadequate control group, and partly because the magnitude of the effect is less than the observed variance in energy consumptions, the passive solar investigations on the Pennylands estate are inconclusive. However the studies done on the Linford site clearly demonstrate that the passive solar design significantly increases the solar contribution to space heating (to 25-40%) in a very cost effective fashion (the passive solar measures have a shorter payback time than some of the insulation measures). Furthermore the detailed modeling work done on the Linford project has led to the detailed calibration of a passive solar model which both predicts the Linford results and predicts that the Pennylands passive solar effects, at about 1000 kWh/year would be too small to unravel from the statistical data. In this sense the two experiments have ended up complementing each other extremely well.

In addition to the monitoring of fuel use the Pennylands project was also subject to other monitoring exercises. BRE carried out a buildability study to see whether there were any problems with building to higher standards of insulation. There was a condensation survey to look for condensation problems more than a year after the buildings were occupied. MKDC undertook a social survey in order to find out whether the residents were typical of other estates in MK and to discover their reactions to the low energy house designs. There was also a limited infiltration survey with a blower door and a thermographic survey with an infra-red camera. Overall these additional monitoring exercises produced a picture of a successful development. The houses were not any more difficult to build, people moved into the Estate because they wanted to be near their work or because they thought it looked nice. After living there for more than a year the thing they liked best about the house was the low fuel bills.

Together the Linford and Pennylands projects have been remarkably successful and have provided firm data on a wide range of extremely cost effective energy saving measures in houses. The Linford project has provided detailed information on U-values, air change rates, patterns of occupancy behaviour together with a well calibrated passive solar model. The Pennylands project has produced hard evidence for the benefits of insulation, low- thermal capacity boilers and measures to reduce infiltration rates. In both experiments the occupants have lived at significantly higher temperatures than those recorded on previous field trials (typical whole house average temperatures over the heating season of 18-19C). This indicates that the occupants were able to afford to heat to reasonable levels of comfort and that the savings recorded were therefore realistic.* The rest of this report sets out the basis for

* Temperatures were nevertheless higher in the better insulated houses.

these laudatory remarks and provides further details of the results obtained, the caveats that need to be placed on them and the difficulties encountered along the way. The structure of the rest of the report can be summarised as follows;

Section 2: Background

This deals with the background to the project, both in terms of the organisations involved (MKDC and OU) and in terms of experimental design. The section includes a discussion of the initial modelling work used to produce the energy brief and of the statistical problems involved with the design of the Pennylands experiment.

Section 3: The Experiment

It is a long way from an initial experimental design brief to having an estate of 170 houses built. This section documents what went on between the two, starting with layout studies and progressing to house designs. This section also contains basic data on the numbers and types of houses actually constructed, including the control groups on Neath Hill

Section 4: Monitoring

All the different types of monitoring carried out on the project are included here and the results of all types, except the fuel data, summarised. For the fuel data there is a description of the processes used for collection, cleaning and storage of data together with overall availability records.

Section 5: Patterns of Energy Consumption

This starts by describing the overall pattern of energy consumption in the different groups of houses. It then proceeds to examine each of the components in turn, including electricity use, fuel used for cooking and fuel for hot water. By the end of this section there is a clear picture of the major differences in fuel use between the groups.

Section 6: Analysis of Results

Here the analysis of the wealth of data is reported. There are three major types of analysis carried out, a statistical analysis of annual energy use, weekly regression and energy balances. Each method has some difficulties and something new to contribute. These results are then pulled together in a synthesis using the NBSLD model developed in conjunction with the Linford work.

Section 7: Energy Savings and Cost-Effectiveness

Here the calculated energy savings for the various measures are brought together with their extra construction costs to estimate the individual payback times.

Section 8: Conclusions

There are several sets of conclusions that can be drawn from this project, conclusions for policy, for house design and for researchers. All these are presented in this section.

Appendices:

In order to avoid cluttering the main report with a great deal of detail a number of self-standing appendices have been prepared that provide further information on particular aspects of the project.

Companion Reports:

There are several other documents referred to in this report which provide complementary information:-

1. Linford Low Energy Houses, ERG 050, a 400 page detailed report on the companion Linford project, available from the Energy Research Group, Open University. The 40 page summary is available separately as ERG 051.
2. Pennyland Social Survey, detailed results of interviews with the Pennyland and Neath Hill residents, available from Milton Keynes Development Corporation.
3. Buildability report on Pennyland and Linford houses, available from the Building Research Establishment.
4. Rapid Thermal Calibration of Houses, a study of the practical and statistical problems of determining the thermal properties of houses, including comments on the Pennyland data, available from the Energy Research Group.

CHAPTER 2

BACKGROUND

CONTENTS

- 2.1 The Energy Consultative Unit
- 2.2 Experimental Design
- 2.3 The Statistical Problem

This chapter outlines the initial design study work and the problems involved in detecting the energy savings.

2. BACKGROUND

This section of the report deals with the background to the project. The first sub-section covers the institutional arrangements and the motives behind the project; the second sets out the reasoning that went on in the design of the project and the third sub-section sets out the basic problem associated with a field trial involving large numbers of houses. With hindsight it is possible to see how the later difficulties were seeded in this pre-project period; at the time the emphasis was on getting the project off the ground and trusting that problems could be dealt with as they arose.

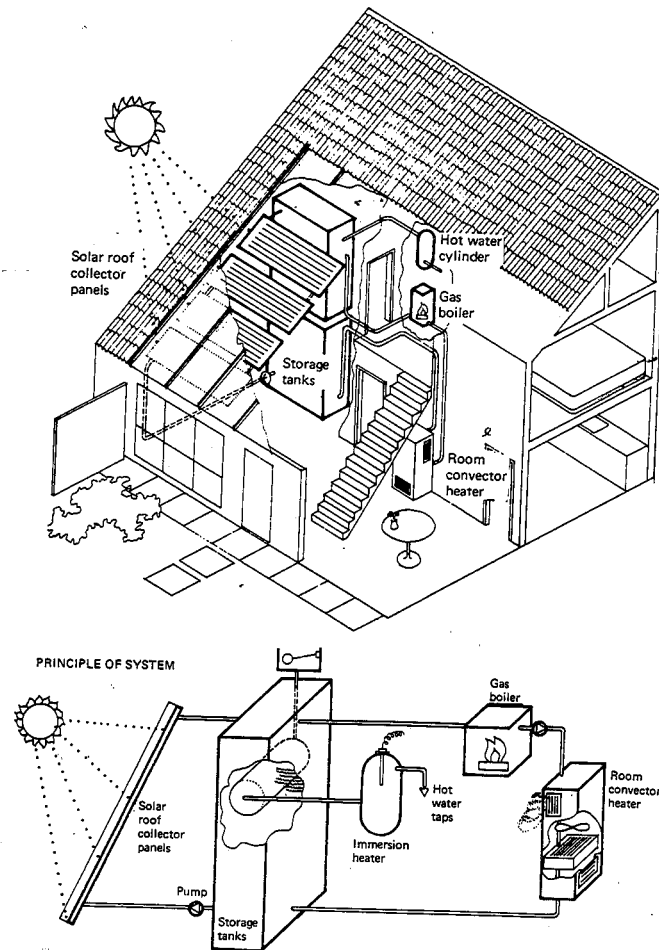
2.1. The Energy Consultative Unit.

Both the Pennyland and Linford projects date back to the first so-called "Energy Crisis" in 1973. Immediately prior to this a small research group, the Energy Research Group (ERG), had been established at the Open University to study energy flows in an industrial economy. With the sudden surge of interest in energy following 1973 this group quickly grew and was able to attract a wide range of funding for projects, most of which were theoretically based. Within a few years it became clear that the paper studies on which ERG had grown needed to be supplemented by a number of practical studies - and the obvious laboratory was the new city of Milton Keynes.

By 1975 the Milton Keynes Development Corporation could see that some of the assumptions that had underlain the Master Planning in the late 1960's were not viable. They undertook a review of the overall plan and as part of that asked ERG to prepare a report on the energy implications for the new city. This began a period of fruitful collaboration between the two organisations.

Independantly the Built Environment Group at the Polytechnic of Central London (PCL) in collaboration with John Doggart at MKDC had designed and commissioned an active solar house at Bradwell. This was completed by 1975 and was successful in that over half the space and water heating was supplied from the solar system. Although this was not a cost effective development it created a great deal of public interest, so much so that over a quarter of all enquiries to MKDC in 1975 were in connection with this solar house. This encouraged the Development Corporation to include "energy conservation" and "energy conscious planning" amongst the objectives of the new city planning.

In 1976 the Energy Consultative Unit was established. The unit consisted



The Bradville Solar House: The general arrangement of components.

Figure 2.1 The Bradville Solar House

Although this worked as designed, further studies suggested that passive solar space heating would be more cost-effective than active solar panels.

of John Doggart from MKDC and Peter Chapman seconded part time from the Open University Energy Research Group. Together they set up a series of projects that have been completed in the ensuing 8 years. A comprehensive report on these projects was published in 1982 (MKDC, 1982). This documents some 44 energy projects that have been undertaken in Milton Keynes. This has laid the foundation for the next stage of work which is the design and construction of an 'Energy Park' at Milton Keynes, an area devoted to both low energy housing and factory design.

Following the success of the solar house two further solar projects were undertaken by the ECU. The first was a study of the cost effectiveness of grouped active-solar heating schemes. It was already clear that an active-solar house could not be made cost effective, largely because of the cost of the hot-water store. It was hoped that by exploiting the returns to scale (i.e. the decrease in unit costs as the size increases) this difficulty could be overcome. In the event this proved not to be the case. (Barrett & Everett, 1977). The study showed that it was far more cost effective to improve the basic house shell (by insulation) than to make use of solar energy captured by an active system.

The other solar project was a study of the layout implications of utilising solar energy, supported by the Housing Development Directorate of the Department of Environment. This project provided the basic groundwork for the Linford and Pennyland schemes. At that time the Linford houses were to be built on a site known as 'Woughton D'. The name changed when the new site was chosen in 1978.

The most important results to come out of the layout study were:-

- (a) a set of solar shadow prints which could be used by an architect so as to avoid significant overshadowing of one building by others. (Illustrated in Figure 2.4 and discussed further later in this section)
- (b) the recognition that passive solar designs were likely to be far more cost effective since they required very little extra "hardware" in or on the house. The passive solar design concept evolved in the course of this project. Essentially it involves a layout which permits southerly orientation with minimum overshadowing and house designs with large south facing glazing in all the main living rooms, the house to be very well insulated and thermally massive so as to act as a store for the solar energy and also reduce the danger of summer overheating.

- (c) the recognition that the most cost effective strategy for reducing house heating demand was to increase insulation, and this shortened the effective heating season and hence the available solar energy
- (d) concrete examples of passive solar layouts which had been developed by an MKDC architect (John Seed) in the process of learning to use and commenting on the ideas and tools developed earlier in the study. Examples of the sketch layouts for Pennyland are shown in figure 2.1.

As a direct result of the work done on this layout study proposals were drawn up for two field trials, proposals which evolved into the Linford and Pennyland projects.

2.2. Experimental Design

It was clear that the research done in the layout study had indicated the next area for investigation, namely the passive solar design concept, but it had also shown that this area was as yet largely unexplored. It was therefore decided to set up two projects, the first of which was regarded as a pilot study for the second. To this end it was decided to make the first a small scheme which could be intensively monitored so as to answer the outstanding questions. The main questions which needed answers at this stage were

- 1 What was the net saving (if any) from south facing glazing?
- 2 To what degree could solar gains be stored in the building fabric? How could this be achieved and what were the critical factors?
- 3 Would such a house produce unacceptable overheating in the summer?
- 4 What was the effect of insulation on the solar contribution to such a house? (A very high level of insulation would reduce the heating season to the point where the solar gains were minimal, too little insulation and the gains would not provide a significant proportion of the heating requirement.)
- 5 What were the costs of implementing a passive solar design?

At this time there was very little data available on which to base any analysis. Bob Everett, then working at PCL, developed a computer model based on the U.S National Bureau of Standards house model (NBSLD, 1978). Using this programme he was able to arrive at some initial answers which suggested that the passive solar concept could be effective, but there

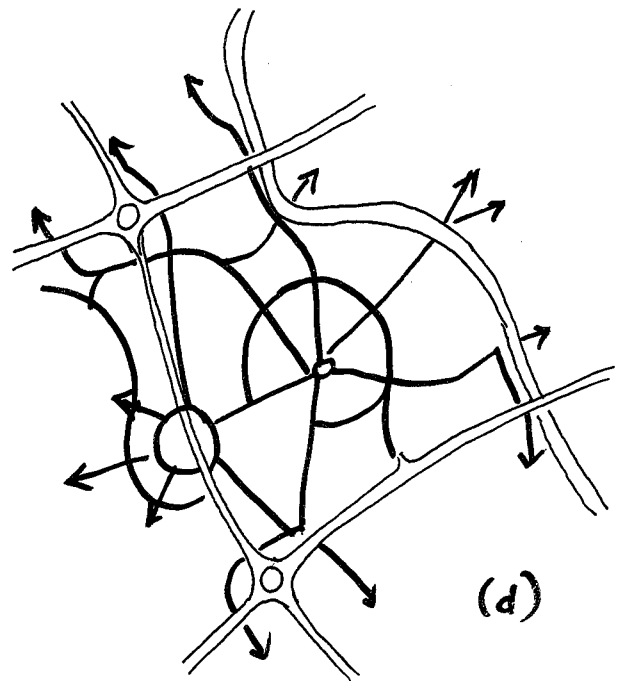
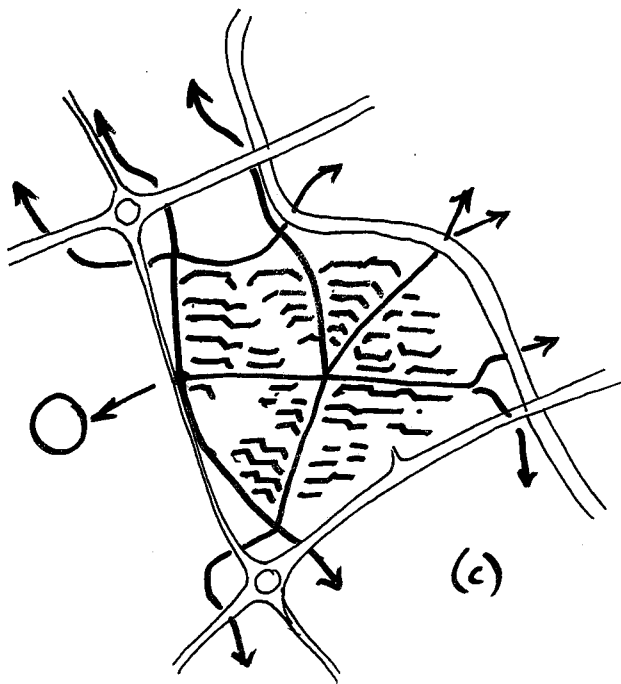
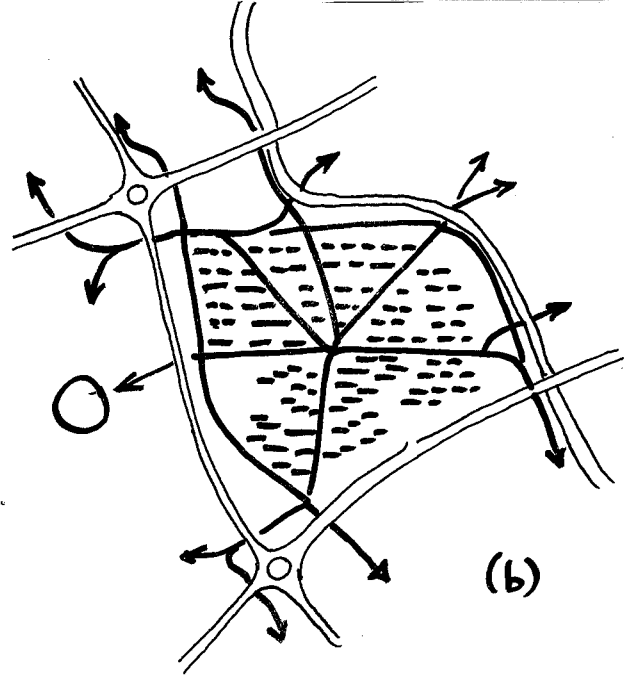
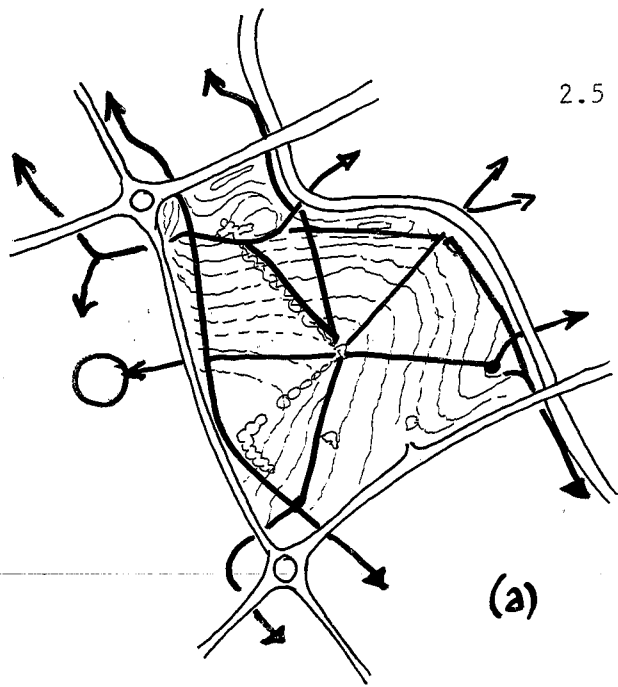
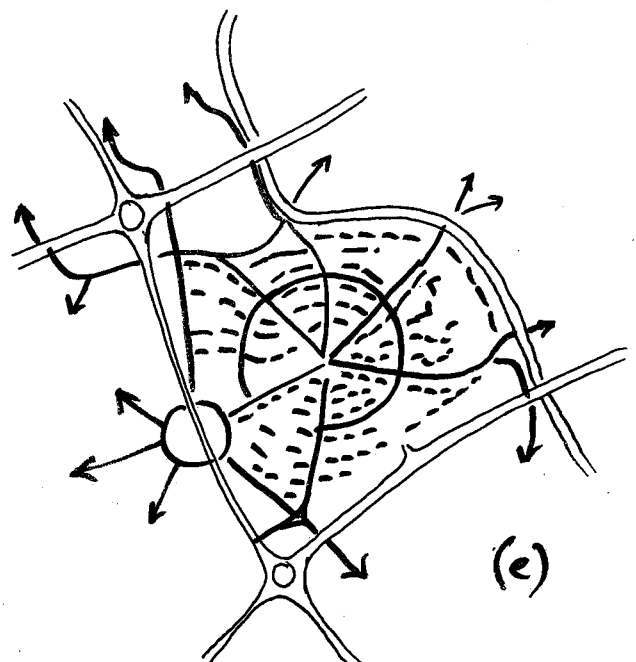


Figure 2.2 Examples of Pennyland layout sketches

- (a) pedestrian routes define structure
- (b) all south orientation
- (c) orientation relaxed; south $\pm 30^\circ$
- (d) new road layout and integrated system with North Hill
- (e) new layout with orientation south $\pm 30^\circ$.



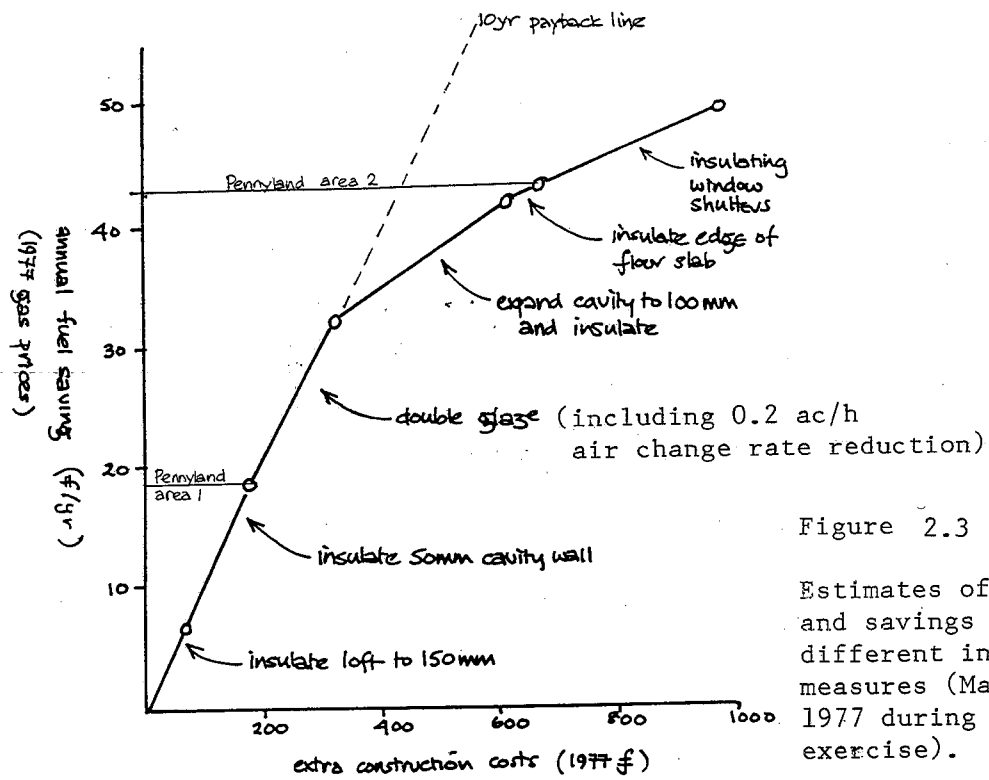


Figure 2.3

Estimates of costs and savings from different insulation measures (Made in 1977 during design exercise).

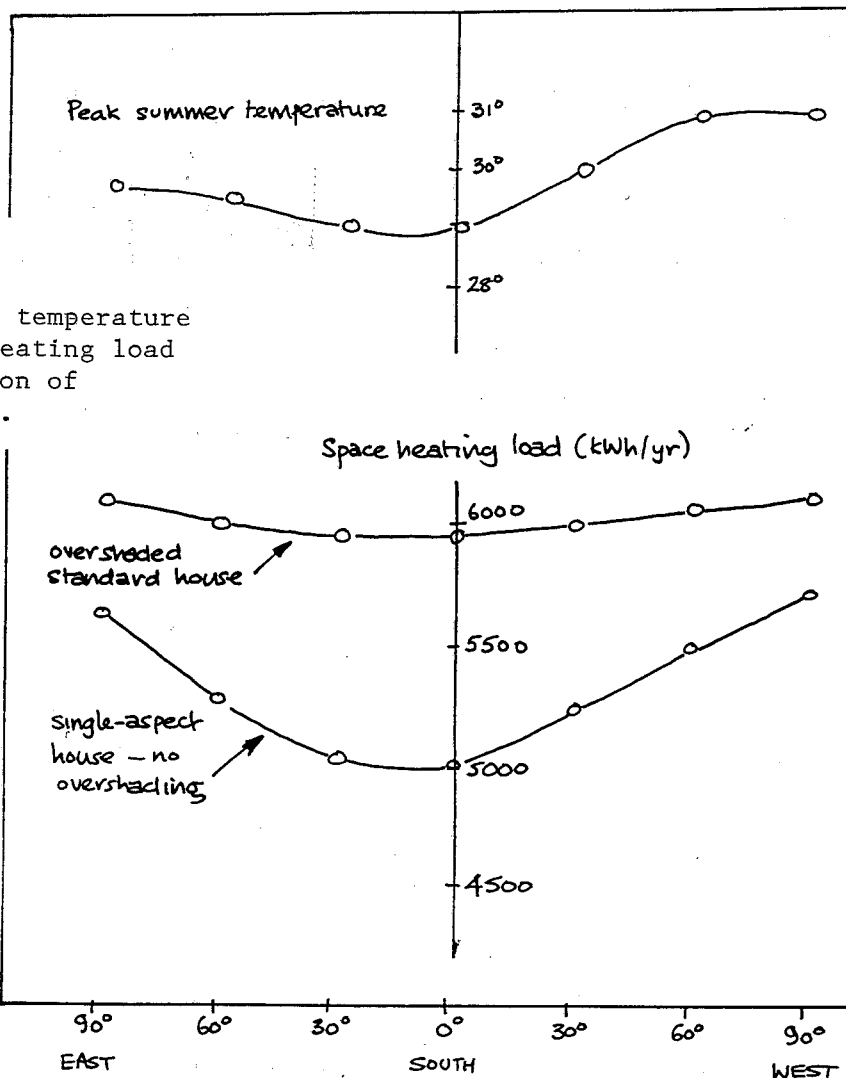


Figure 2.4

Peak summer temperature and space heating load as a function of orientation.

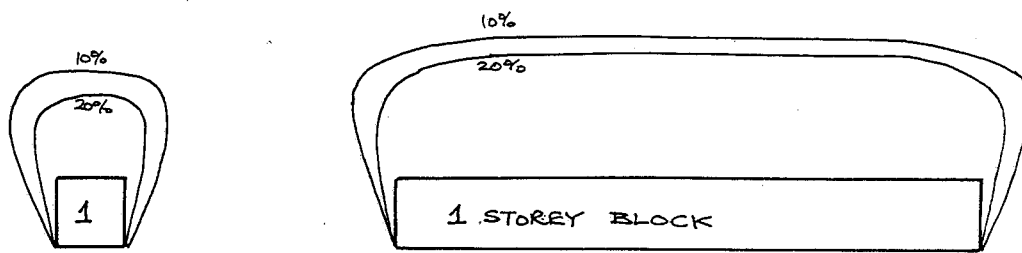


Figure 2.5 Solar Shadow Prints showing percentage reduction in solar radiation through ground floor window over heating season as a function of proximity to another building.

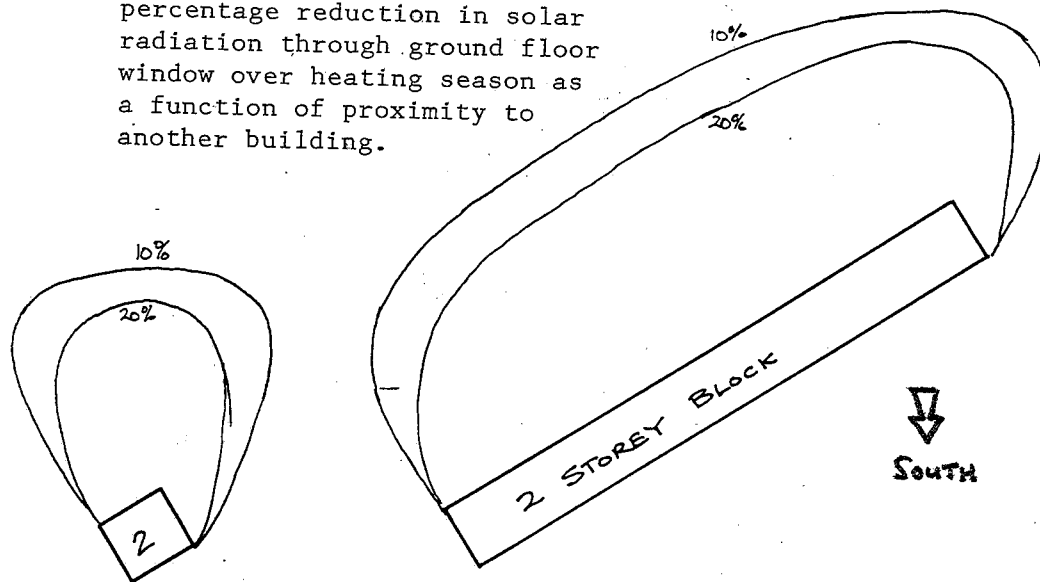


Figure 2.6

Typical Pennyland facade showing shadow of roofline on wall. Time - 2.00 p.m. on a January afternoon.



was not enough data to have confidence in these initial conclusions. It was also this programme that was used to generate the solar shadow prints and begin the process of evaluating alternative house designs. The evaluations completed in this way can be summarised as follows;

Insulation Analysis

The cost effectiveness of insulation measures was deduced using a simple rule of thumb derived from degree day calculations that a reduction of 1 W/K in the total house heat loss would save about 40 kWh/year useful space heating energy. Starting from the 1976 Building regulations (unfilled cavity wall, single glazing and 50mm roof insulation) the costs and estimated savings of a range of measures were calculated for new houses. The results are shown plotted in order of payback-times in figure 2.3. Roof insulation was limited to 150 mm as it was thought that a greater thickness (combined with a poorly installed or absent vapour barrier in the first floor ceiling) might cause condensation in the loft space. The levels of insulation chosen for the two Pennyland standards are shown on the graph. The first is conservative and is equivalent to the levels later included in the 1982 Building Regulations, the second is more adventurous and yet appears to have a reasonable payback period.

Orientation analysis

Initially it was thought that the passive solar house had to face rigidly south, a constraint that produced very dreary estate layouts. The early modelling studies showed that there was in fact very little change in space heating requirements as the house orientation was varied between $\pm 45^\circ$ around due south. Indeed the minimum energy requirements occurred for an orientation slightly East of south, as shown in figure 2.4. This result had a major impact on the estate layout work since it freed the architect from the most binding constraint. (This can be seen by comparing layouts (b) and (c) in figure 2.2).

Overshading analysis

Figure 2.5 shows examples of the "solar footprints" developed for use in the layout studies. Their application to the Pennyland estate will be illustrated further in section 3.1. For the present it is sufficient to note that the prints were developed so as to ensure that the midwinter sun should just graze the roofline of one row of houses in order to penetrate the ground floor windows of the next row. This is illustrated in practice in figure 2.6.

Window area

Assessing the effect of window areas on a house energy consumption is a rather complex process. The outcome depends upon the type of glazing used, the U-value of the wall replaced by glazing, the length of heating season and the solar gains made through the glazing. In order to make meaningful comparisons a set of insulation standards was chosen to accompany single and double glazing standards (it would not make much sense to install double glazing in a house with no loft insulation). Then a series of house designs were evaluated using the NBSLD model. The sequence is illustrated schematically in Figure 2.7 and in energy terms in Figure 2.8. The sequence of improvements shown is;

- a) first the house is insulated
- b) the overshadowing is removed and the house orientated south
- c) the glazing is concentrated on the south side (no increase in glazing area).
- d) at this stage the effect of changing window area is explored
- e) the house is insulated to a higher standard including double glazing
- f) again the effect of varying the glazing area is explored

What this analysis clearly showed is that insulation is far more significant than the passive solar features in reducing the space heating demand. Further preliminary calculations of the peak summer temperatures indicated that it was likely to be optimal to keep the glazing area on the south face to less than 50%. (For further details see Everett 1980)

From all these calculations the specification for the Passive Solar houses began to emerge. As indicated earlier in this section the initial plans were to try out the concept on the small scale site (then Woughton-D) starting in 1977 and to get preliminary results before work on Pennyland was scheduled to begin in 1980. Designs for the Woughton houses were produced by Martin Richardson in 1978, but by then there were significant difficulties in accommodating the developer on the site. The small scale project was therefore delayed and transferred to another site - the Linford site. Meanwhile the Pennyland scheme was brought forward in time. Design work proceeded intensively through 1977 and 1978 for a start on site in 1979. The change in scheduling of the two projects is illustrated in figure 2.9. The two immediate implications of these changes were

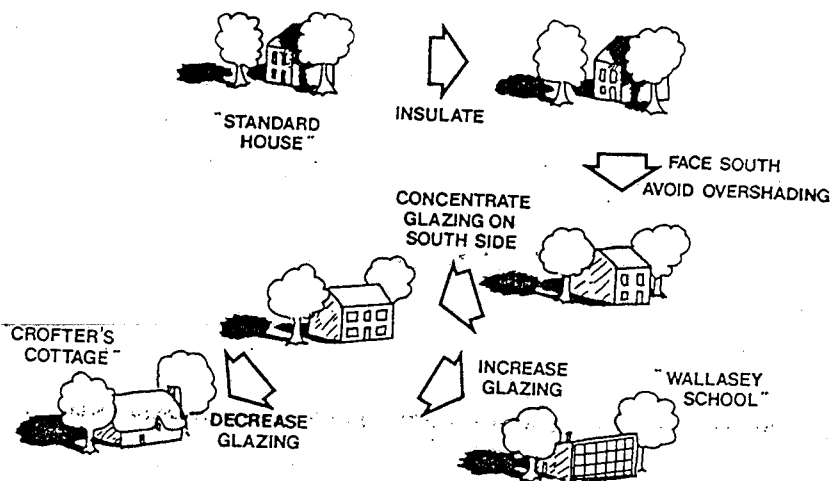


Figure 2.7. Energy Saving Steps in Computer Analysis

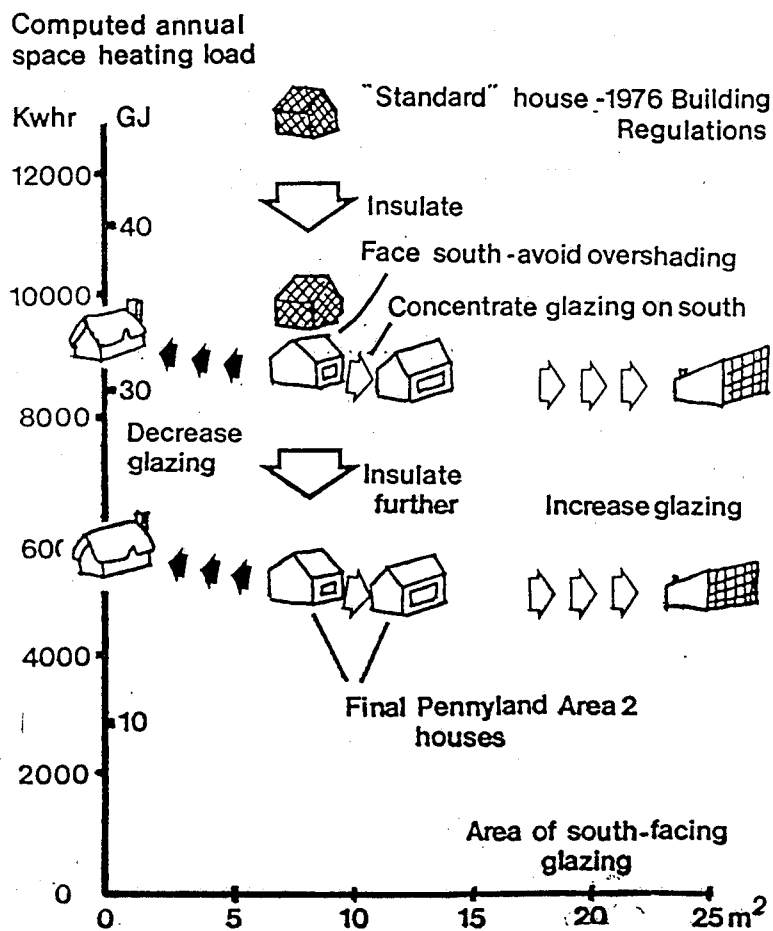
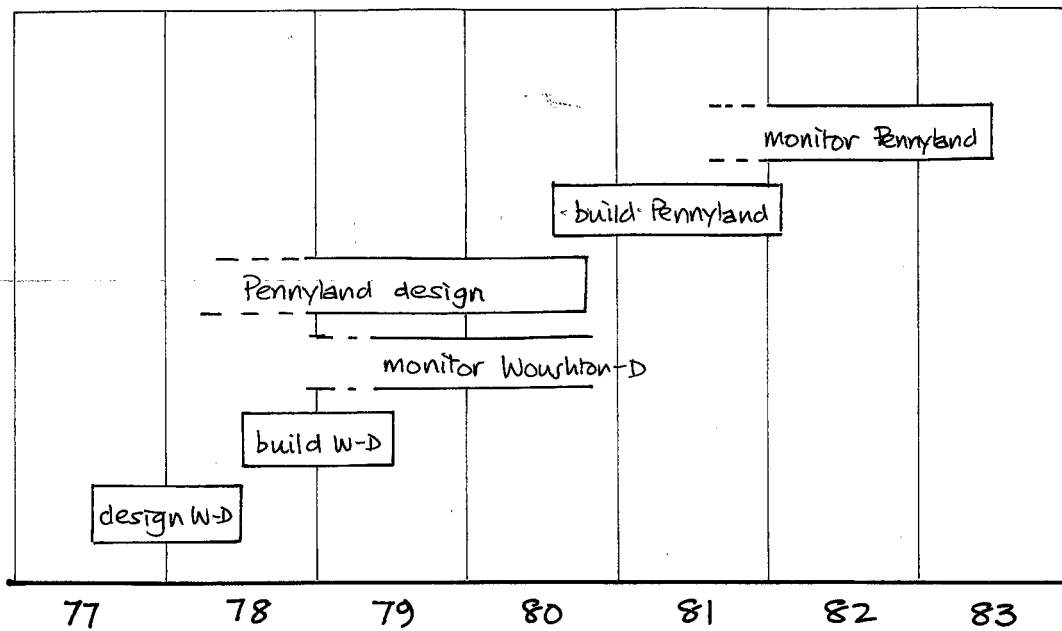
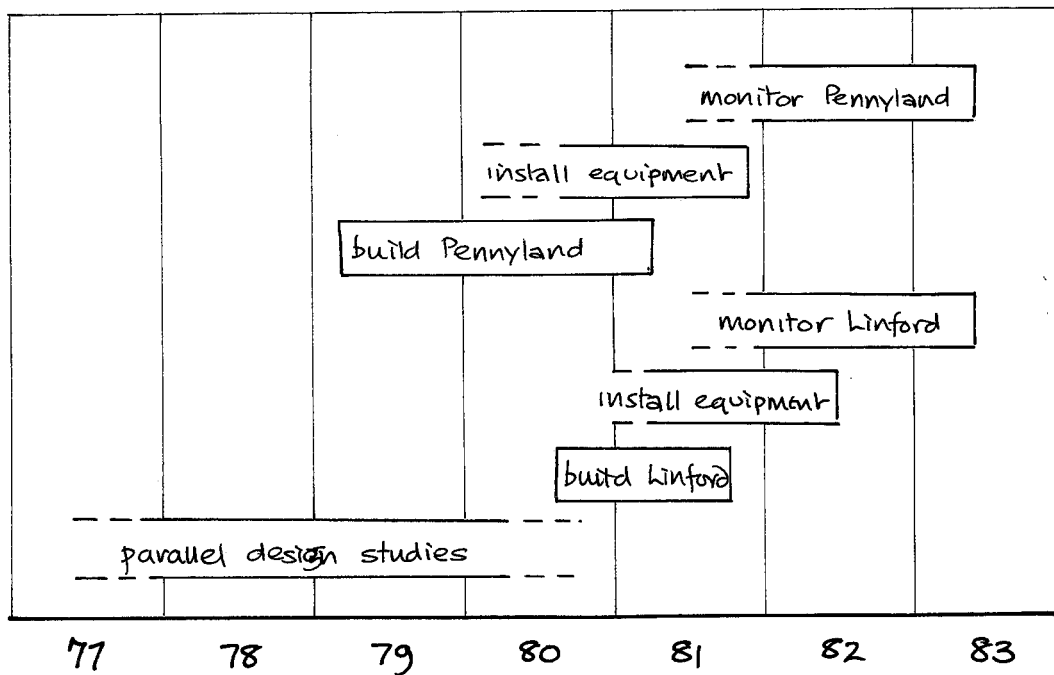


Figure 2.8 Computed space heating demands as a function of insulation level and south-facing window area.



(a) planned development sequence



(b) actual development sequence

Figure 2.9 The planned and actual chronologies of the projects

- a) the Pennyland project would have to proceed on the basis of the computer modelling studies
- b) the research teams were going to be stretched to install and commission all the necessary monitoring equipment in 1979-80.

Further details of the estate layout and house designs are described in chapter 3. However before then there is another feature of the experimental design which requires explanation

2.3. The statistical problem

In concept the Pennyland experiment was to be very simple. There were to be two standards of insulation on the estate and within each insulation group there were to be two house types; a more or less normal house type and a passive solar house type. The normal house type has a narrower frontage and a 40-60% split of glazing areas on north and south facades; in the rest of this report it is referred to as a dual aspect house. The passive solar houses have a wider frontage, to allow the living rooms and bedrooms to be concentrated on the south facade, and has about 75% of the glazing concentrated on the south side; this house is referred to as a single aspect house. In the initial design both house types had the same total glazing area, so in going from a dual aspect to a single aspect house one was testing the strategy of concentrating glazing on the south face.

The lower insulation area of Pennyland is referred to as Pennyland 1, Pennyland 2 being the well insulated section. We thus have four groups, single and dual aspect houses in Pennyland 1 and 2. Given a total of 177 houses it was expected that one could get four groups of 40 which on the face of it should be enough to come up with statistically significant conclusions.

There are two flaws in this chain of reasoning. The first flaw will be amplified in section 3 and concerns the many other features of the Pennyland houses which makes them different from each other. There are houses of different size (five different sizes in fact), there are significant differences in orientation (for layout reasons some houses were eventually orientated east-west) and there are different degrees of terracing (houses can be end terrace, mid terrace or part of a staggered terrace; this is illustrated and discussed in further detail in section 3.2). These physical differences mean that at the end of the day it turns out to be quite difficult to get groups of 20 houses that are the same except for the major variables (insulation and house aspect).

The second flaw in the reasoning is concerned with the statistics of the situation. This problem was actually identified before the monitoring strategy was finalised and was therefore incorporated into the experiment. The difficulty centres around the fact that given a group of apparently identical houses it is usual to find that the energy consumption in the houses varies by a factor of 3:1, sometimes 4:1. In numbers this means that a house design which has an average fuel use of say 10000 kWh/yr will, in use, give rise to a range of fuel consumption from 5500 kWh/yr to 16500 kWh/yr, possibly from 5000 to 20000 kWh/yr. Examples of this sort of spread in results from field trials are illustrated in Appendix 2. Now if one is expecting differences in energy consumption from, say, a set of insulation measures, of about 4000 kWh then it is not unreasonable to be able to detect the difference even given the large spread of consumptions for each group. This is schematically illustrated in Figure 2.10(a) However the passive solar measures incorporated in the Pennyland experiment are not expected to make a difference of more than 1000 kWh/yr. In this case trying to detect the difference in amongst the wide spread of consumption becomes problematic, to put it mildly. This is illustrated in figure 2.10(b).

In fact Figure 2.10 makes the problem look much easier than it is in practice. It does so by representing the distribution of fuel use as a nice smooth curve. Field trials actually give rise to the sort of histograms previously shown in figure 1.8.

This issue is addressed in Appendix 2 and analysed there. The analysis focusses on the problem of estimating how many houses have to be in a sample in order to be confident that an energy difference of a certain magnitude has been detected. The magnitude is expressed as a function of the standard deviation (the width) of the statistical distribution. The key result is shown in Figure 2.1. The curves are levels of statistical confidence. Thus, for example, a sample of 30 houses is sufficient to give 95% confidence in detecting a difference in energy consumption equivalent to half a standard deviation. Now the sort of standard deviations observed in field trials is about 4500 kWh/yr, so for a 95% level of confidence groups of 30 houses are adequate for detecting energy differences of 2250 kWh/yr or more. Put another way it is necessary to have groups of at least 30 houses to be 95% certain that an observed difference in energy use of about 2250 kWh/yr is a real difference and not simply an artefact of the statistical variation in energy use from

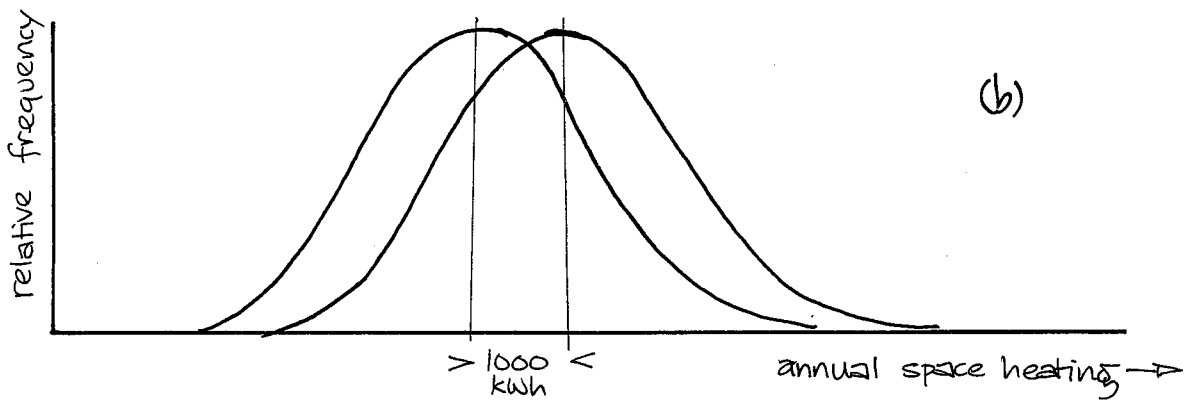
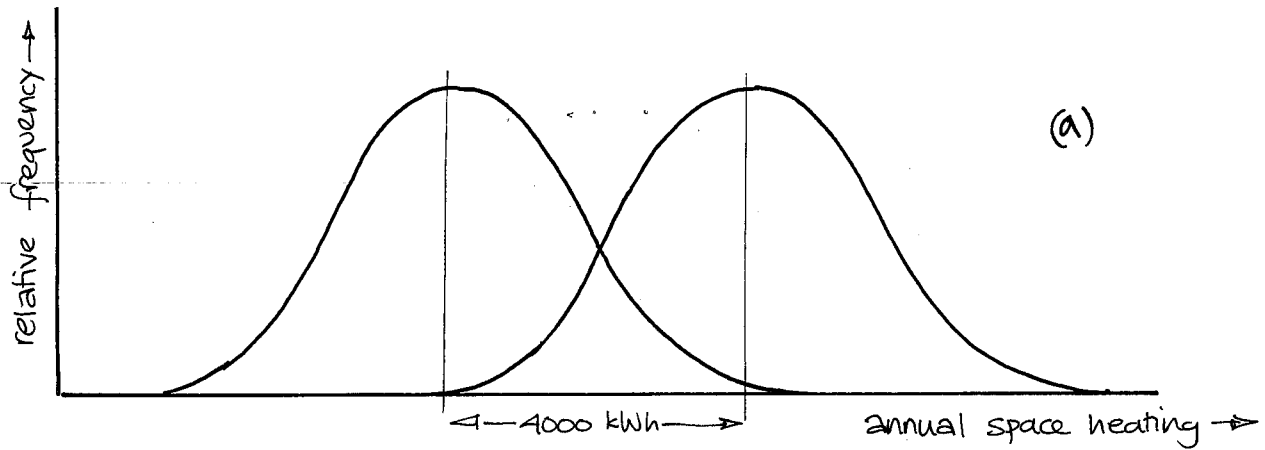


Figure 2.10 Illustrating the relative magnitudes of the variance of the distribution of space heating and the expected differences between
 (a) better insulated houses & normal
 (b) better solar houses & normal

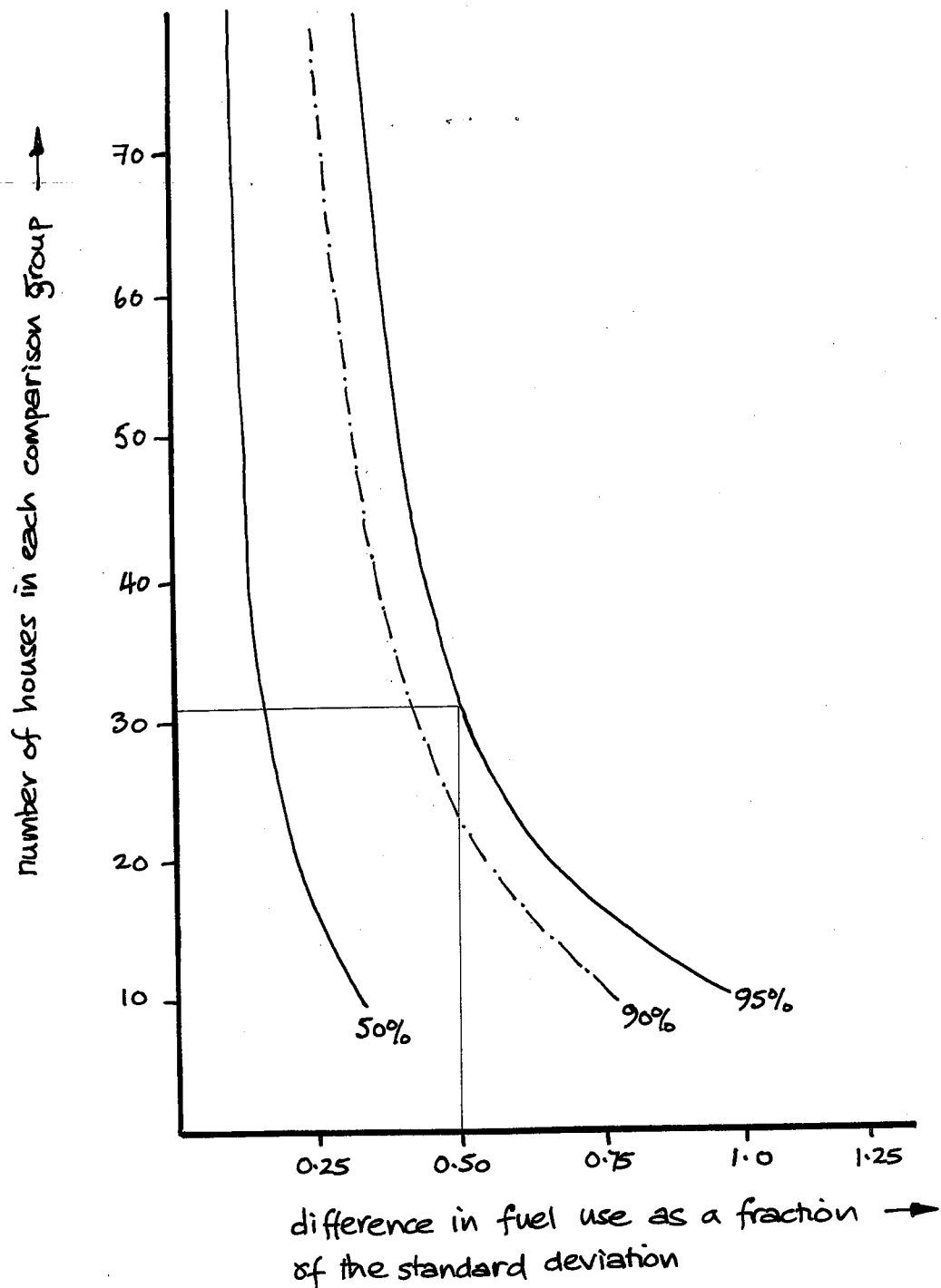


Figure 2.11 The relationship between the statistical confidence (% shown by curves) associated with a given difference in fuel use (expressed as a fraction of the standard deviation) and the number of houses in each comparison group

one house to another. To get a 95% confidence on the projected passive solar difference of about 1000 kWh/yr would require groups of about 300 identical houses! Even worse, this is only 95% confidence that we have some energy savings. To actually quantify them requires more houses still!

This is the basic statistical problem of this experiment. It is not just confined to the energy consumptions. Such things as estimating the extra construction costs are also subject to uncertainties and need a large number of houses to average out over.

It was thus clear that it was not sufficient simply to monitor the gross fuel consumptions of the houses. It was necessary to monitor other variables so that a large proportion of the variance in the observed energy use could be corrected for. In order to do this it was necessary to have estimates of energy used for cooking, water heating and some sort of measurement of internal temperature. Heat meters were installed to measure space heating directly.

The effect of using space heating energy consumptions corrected for a number of sources of variance rather than the raw gas consumption data can be seen in figure 2.12. This large reduction in spreads of consumption has allowed comparisons to be made with groups of only about 10-20 houses.

Even so, the passive solar comparisons have not really produced any statistically hard answers and another approach was envisaged as well. This was to undertake some kind of 'house characterisation', extracting the basic response of each house type to changes in external temperature and solar radiation by comparing weekly energy consumptions. In doing this it was hoped that the house total heat loss coefficient and an equivalent 'solar aperture' relating solar gains into the house to incident solar radiation, could be extracted by statistical means.

Knowing the absolute solar gains into a house on any week, a computer model could then be used to calculate the marginal solar gains, or the actual annual savings of space heating energy (see figure 2.13 for a comparison of these terms). This process is by no means easy since the absolute solar gains into a house are essentially a negative quantity, space heating energy that has not been used. It is thus necessary to know a great deal about the house in order to make sure that the observed energy change is not caused by some other factor. The best results using this method have come from the Linford test house where heat flows through the floor and due to the continuously varying air infiltration rate have been directly measured. The calculated energy savings for this project given in Chapter 6 are very largely dependent on these Linford results.

The process of 'house characterisation' in this project has only been of limited use because of the fairly crude monitoring actually installed, but when the results are taken in conjunction with the Linford test house and occupied house results, it becomes clear how much monitoring equipment is necessary to produce a given answer. This issue is dealt with in the companion Rapid Thermal Calibration report.

The detailed strategy of monitoring and the equipment installed is all described in Chapter 4.

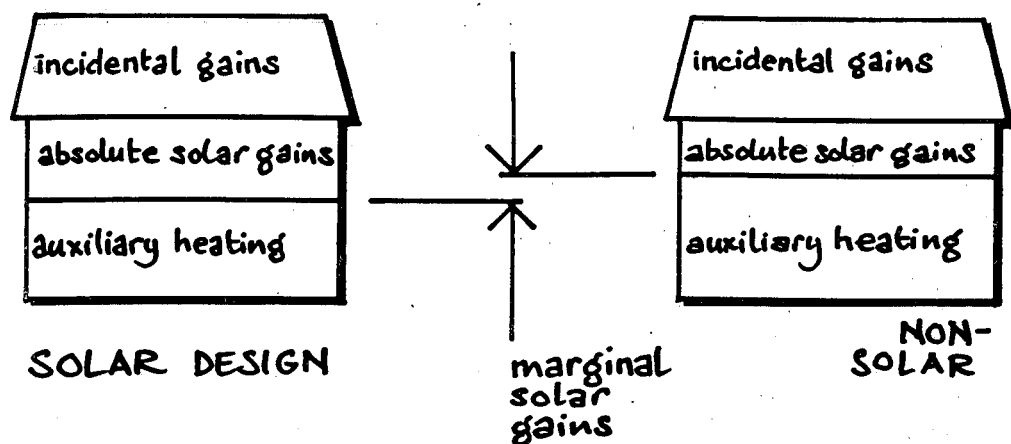
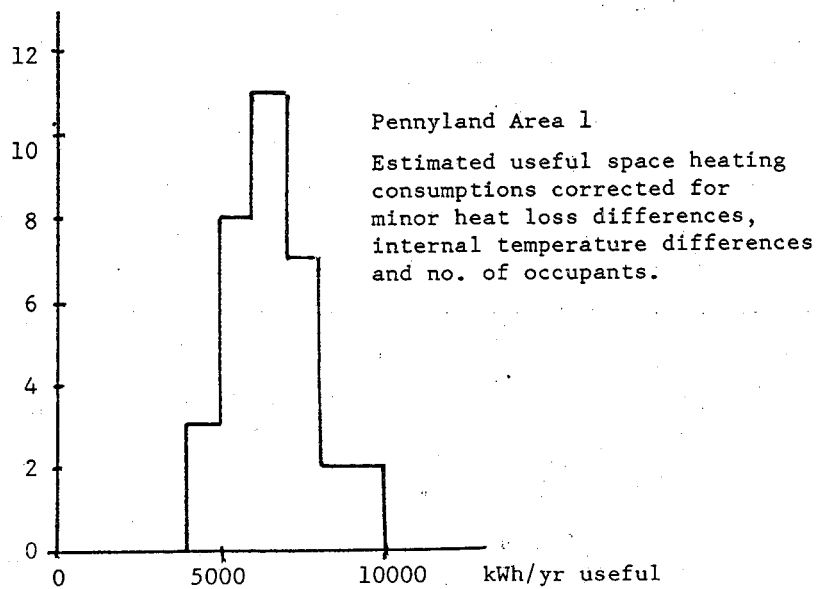
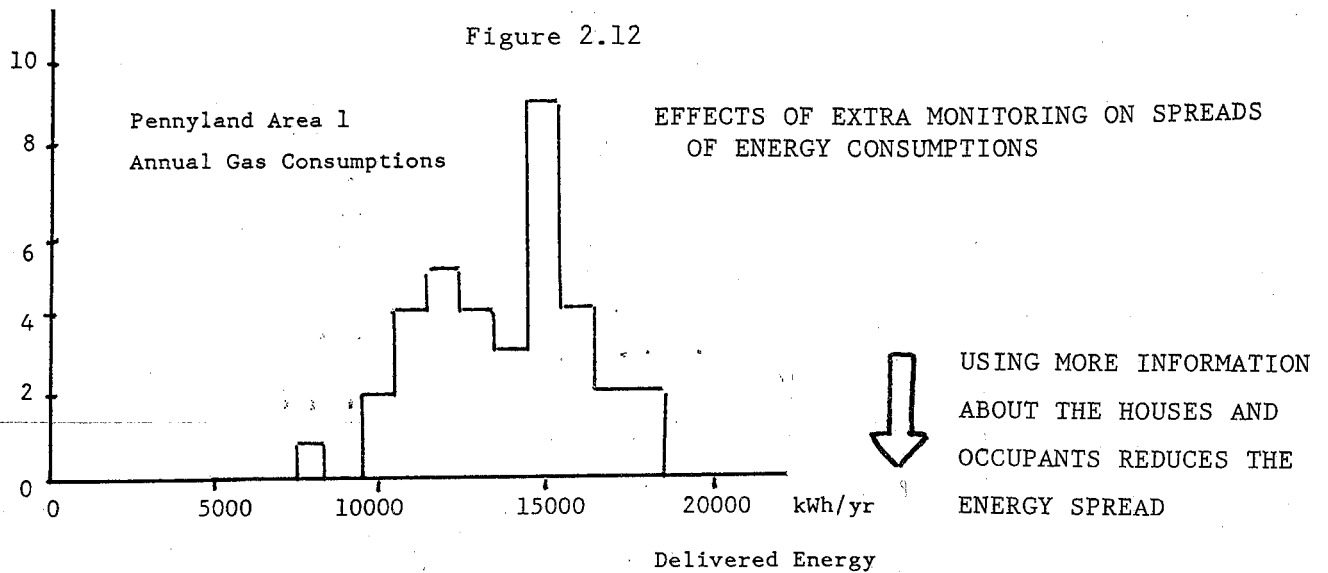


Figure 2.13 Absolute and Marginal Solar Gains

Every house is to some extent solar heated with absolute solar gains. What really matters is the difference in annual energy use between a solar and non-solar design. This is the marginal solar gain.

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CHAPTER 3

THE EXPERIMENT

CONTENTS

- 3.1 Pennyland Layout
- 3.2 House Design at Pennyland
- 3.3 The Control - Neath Hill

This chapter describes in detail the layout of the Pennyland estate and the house plans and construction details of both the Pennyland and Neath Hill houses.

3. THE EXPERIMENT

This section sets out, in some detail, what was actually built at Pennyland and how this compared with the experimental design. There is also an equivalent description of the Neath Hill estate so that by the end of the section it is possible to draw up a detailed comparison of the houses on Pennyland 1, Pennyland 2 and Neath Hill. This is crucial to understanding the issues involved in analysing the results.

3.1. Pennyland Layout

As indicated in section 2.1 the roots of the Pennyland experiment lay in the "Layout Study" undertaken for the Dept. Environment in 1976/77. The purpose of that study was to see to what degree housing layout could be adjusted so as to maximise solar energy collection. This is an attractive approach since, in principle at least, a different housing layout will not carry any cost penalty. At a time when harnessing "alternative" or "ambient" energy sources was highly fashionable it also seemed prudent to consider designing new housing estates so that either now or at some point in the future it was possible to capture a significant proportion of the solar energy. (This is an opportunity cost argument; it costs very little to create the opportunity to do something which, whilst probably not cost effective now, may well be attractive at some future time.) There was thus a great deal of attention paid to both the process of designing the Pennyland layout and also the effectiveness of the resulting layout.

In the layout study the solar shadow prints were developed and an energy brief began to emerge in the dialogue between energy researchers and the architect (John Seed) involved. The layout brief turned out to be simply;

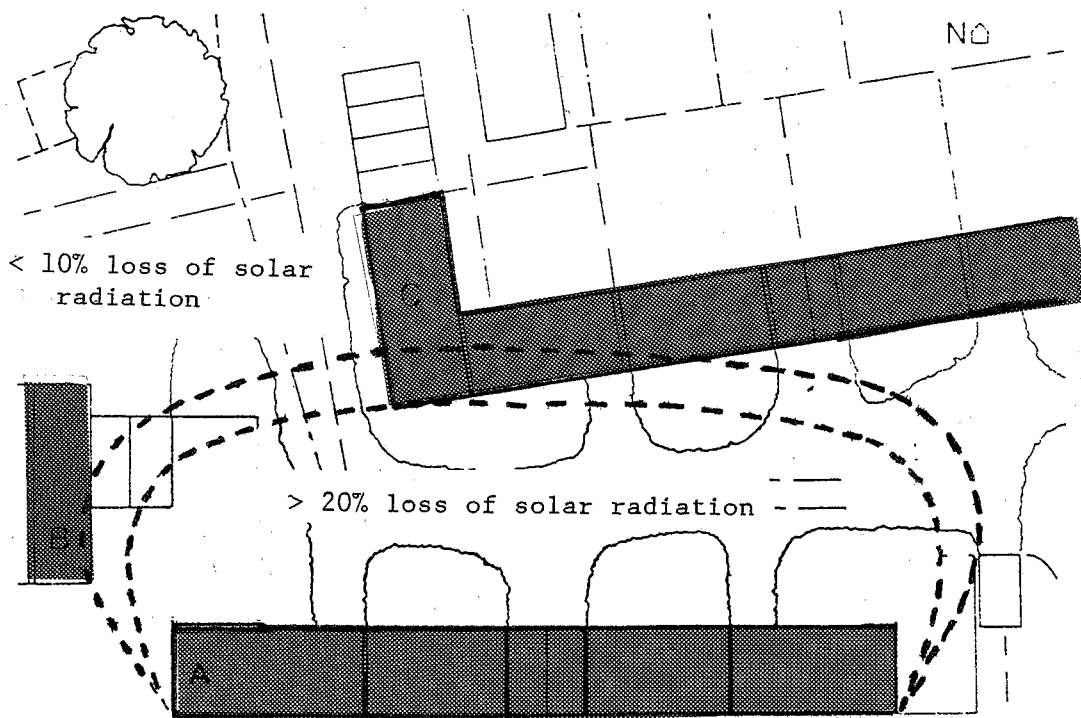
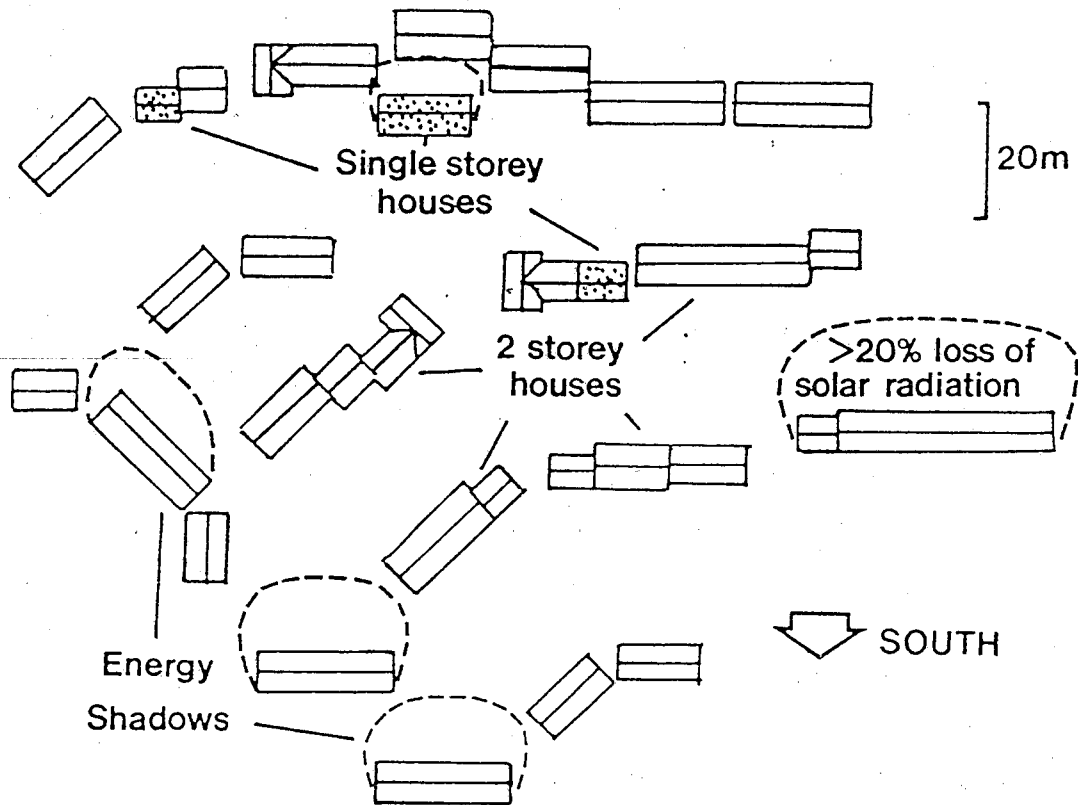
- (i) houses to face south $\pm 30^\circ$
- (ii) overshadowing to cause no more than 10% solar energy loss

With these constraints the Martin Centre at Cambridge were able to show that the maximum theoretical housing density would be 30- 40 houses per hectare (Martin Centre, 1977). In fact the maximum density required fairly narrow frontage houses (so as to accommodate the necessary block-to-block spacing) which would not be optimal for a passive solar house design (where large south facing glazing areas are required). Exploring the implications of these constraints on the Pennyland site was complicated by the fact that the site sloped down to the North (1 in 20). This effectively increased the shadow length of houses and required very careful design work later (this is referred to again in the house design section).

Figures 3.1 and 3.2 illustrate the use of the solar shadow prints in designing the layout. The technique is particularly helpful in sorting out "tight" corners where several buildings come close together, as in figure 3.2. The initial layout, derived from the above brief and with additional objectives of visually attractive layout and encouraging the use of cycle and foot paths, is illustrated in figure 3.3. In this layout the terraces are up to eight houses long and use is made of the $\pm 30^\circ$ variation in orientation to reduce monotony. This layout had an overall density of 35 houses per hectare. All the houses in the design were of the passive solar type, i.e. single aspect.

At about this time it seemed that there would be an imminent change of government, and with it a change of housing policy. As a result the Development Corporation decided to reduce the scope of and bring forward some of its public sector schemes, amongst them Pennyland. At this time it was decided to concentrate the energy experiments on the 177 houses in the north east area of the site, leaving the southerly part available for private sector development. In the process of reviewing the plans for the Pennyland estate the initial layout was criticised on several grounds. The most significant were that the pleasant northerly views had been ignored and that the layout gave too little sense of community. Earlier experience in Milton Keynes had shown that where estates failed to generate a sense of community then there was a high level of dissatisfaction and turnover in occupants. The northerly view from the Pennyland estate was significant since it looked out over the Grand Union Canal and the linear Park, a feature that runs through Milton Keynes. To ignore such a feature of a site was obviously bad practice. These details are important since they indicate the degree to which in a "real" development the energy objectives have to be integrated into a wide range of other objectives.

In order to take note of the northerly views it was necessary to introduce dual aspect houses into the estate, especially along the northern edge. The houses were clustered into groups of 25-40, thereby generating the sense of community, and a more southerly orientation adopted, as shown in Figure 3.4. At about this stage a more detailed analysis was made of the block-to-block spacing so as to increase the overall density. The house roof lines were lowered a little (see section 3.2) and the block spacing worked out such that the midday, mid-winter sun cast a shadow below the bottom of the living room windows of the next block. A mixture of one and two storey houses was included in the estate and advantage was taken of this to increase the density of the estate: a single storey house does not have to be so far away from the houses to the north to avoid overshadowing them. The accuracy to which these



Figs. 3.1 and 3.2 The use of the solar shadow prints in laying out the estate.



Figure 3.3

The Initial Pennyland
Layout



Figure 3.4

An Intermediate Layout
of the Estate

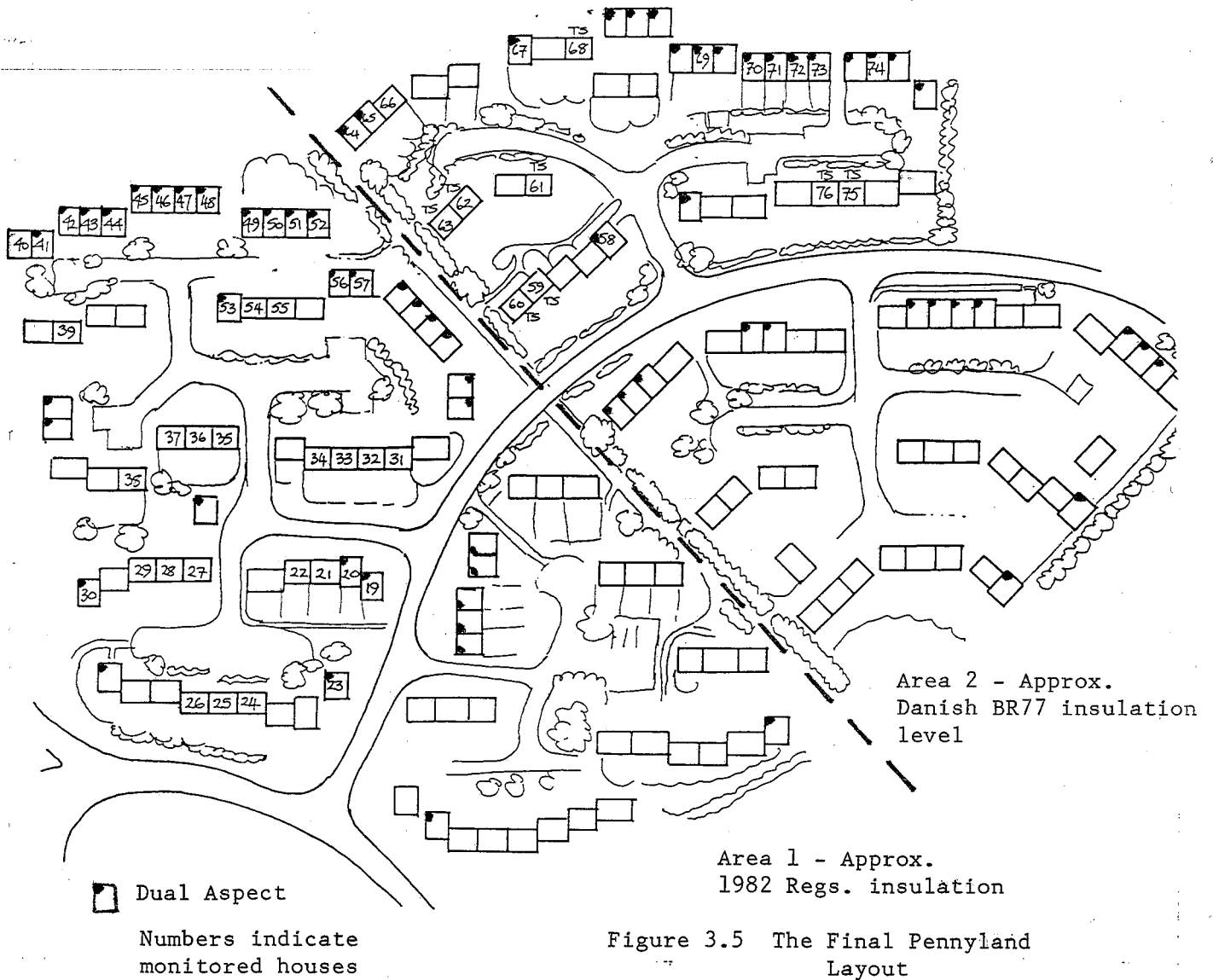


Figure 3.5 The Final Pennyland
Layout

calculations were made is illustrated in figure 2.6 which shows such a shadow in January.

However this scheme came in for further criticism. It was simply too monotonous and would not fit with the more "organic" style being implemented in other areas of north Milton Keynes (see for example the layout of Neath Hill and Great Linford in figure 1.5.) This time the layout modifications necessary could only be achieved by relaxing the orientation constraints (to $\pm 45^\circ$) and allowing the occasional house or group of houses to have an east/west orientation. It is possible that had there been more time the layout could have maintained the solar constraints, but time was not available; there was a considerable pressure to shorten the design time and start on site.

Figure 3.5 shows the final layout of the estate, indicating the dual and single aspect houses. The house numbers are the identification numbers of those houses with detailed monitoring.

Figure 3.6 shows how the stepping and breaking up of the terrace has avoided the monotonous slab terrace design that would have been easy to build. This has given the houses a sense of individuality, obviously with an eye to their possible sale.

The Pennyland estate maintained the objectives of providing short and effective pedestrian and cycle paths with roads following less direct routes. It was therefore appropriate that the division between the two insulation standards should be marked by the main pedestrian route through this part of the estate.

There is no doubt that the resulting layout of Pennyland is a very good compromise between the "pure energy" objectives and the practical realities of building an estate that is pleasant to live in. As will become clear later the Pennyland estate is enjoyed by the residents. It is also clear that the estate has met most of the solar objectives effectively. There is very little overshadowing and the majority of the houses are of the single aspect type facing south $\pm 45^\circ$.

However as an experimental site it is not so good! The point is simply that a "good" experiment requires fairly large numbers of identical houses that can be compared. This is no longer available on the Pennyland layout. The terracing has been reduced to blocks of 2 or 3 houses; where there are longer terraces they are staggered and this introduces differences in the fabric heat losses of the houses. There are now a significant range of house orientations and house sizes. It is actually



Fig.3.6 Stepping and curving the terraces has avoided a monotonous estate design



Figure 3.7

Dual aspect houses were used on the northern edge of the estate giving views of the Grand Union Canal

difficult to get comparable groups of 10 identical houses. (See summary at end of section 3.2) This has created the need for more analysis work.

3.2. House Design at Pennyland

Early in the process of estate design it was necessary to establish the basic passive solar house design, the single aspect house. The passive solar concept relies upon solar gains to provide a large fraction of the space heating requirements. In a normal house solar gains are not efficiently used since some of the living rooms and bedrooms do not receive significant solar gains. Since these rooms have to be kept comfortable they have to be heated, and so too are the rooms with solar gains. The installation of thermostatic radiator valves on rooms with large solar gains improves the situation somewhat, but the essential problem remains, namely that the solar gains are not uniformly distributed over all the occupied rooms of the house.

In the single aspect house design this problem is solved by designing the internal layout so that ALL the living rooms and bedrooms have significant solar gains. Of course some rooms have to be positioned against the north face of the building. These are chosen to be the kitchen, bathroom, toilets and storage rooms. The kitchen and bathroom are both rooms usually adequately heated by the incidental gains released in them; toilets and storage rooms do not require the same high level of comfort. Additionally the stairwell and connecting spaces are also set against the North face of the building.

The internal layout of the single aspect house is shown in figure 3.8 and that of the dual aspect type in figure 3.9.

There are a number of features worth noting.

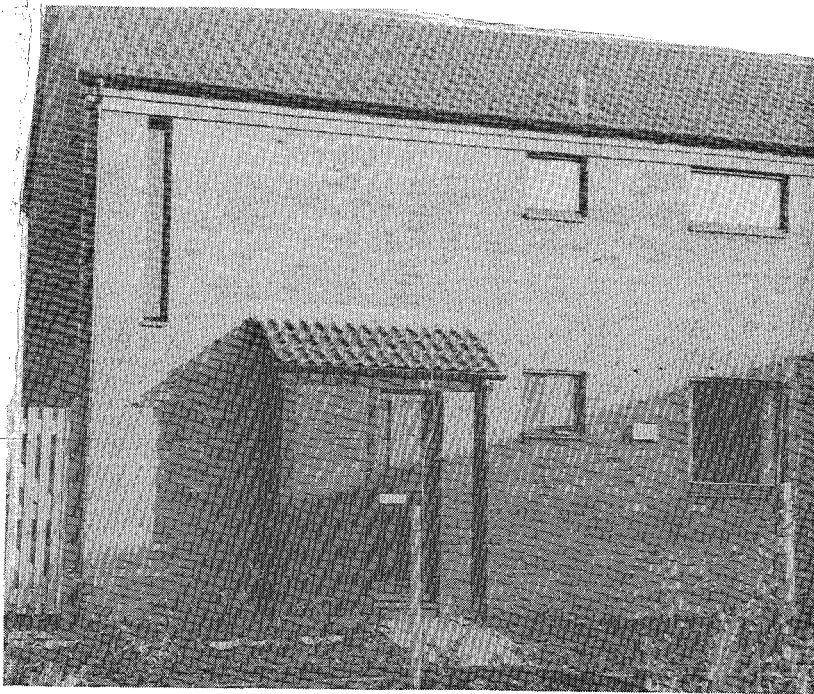
First the single aspect house has a significantly wider frontage. This has two effects. The extra frontage means that the houses are further apart and so there is, in theory at least, an increase in the cost of roads, drainage and other services provided to these type of houses. In practice this effect was not significant in that the Pennyland estate did not have higher road or service costs than normal. Presumably this is because the other factors affecting road and service costs dominate the final costs and the architect was sufficiently skilled to reduce road lengths. The other effect of the wider frontage is to increase the fabric loss of the house, especially in the case of a mid- terrace house.

Second the dual aspect house provides easier access from both north and south sides. In fact two variants of the basic dual aspect house were finally used, type 5d with the front door on the south and 5e with the front door on the north. As pointed out above, one of the main design features of the single aspect houses was that the circulation spaces were almost all on the North side of the house. This forced the front doors of these houses to be on the North side. However, this is the least attractive facade visually since it is mostly brick wall - the windows on the north face are kept very small. To some degree this unattractiveness of the north face has been counteracted by careful design of the entrance porch. The porch also includes the meter cupboard which, as is now usual, can be read from outside the house. This porch also provides some shelter for the front door from wind.

Third the original concept of the single and dual aspect houses was that they would both have the same total glazing area. This meant that there would not be any additional fabric loss due to differences in total glazing area*. In practice it was found necessary to increase the size of the north-facing windows on the single aspect houses, and the total glazing area in fact became about 30% greater than that of the dual aspect houses. This is an important factor. In the original concept, what was to be tested was the energy effect of moving glazing from the north to the south face; this was expected to result in an energy bonus. In practice what has been tested is an increase in the south-facing glazing area. This has no significant energy effect using ordinary double-glazed windows; the increased solar gains are balanced by the increased fabric loss (since the window replaces wall). The energy balance of a south-facing double-glazed window is roughly zero! Thus the net "passive solar" difference between the single and dual aspect houses at Pennyland is (predictably) found to be \pm a few hundred kWh.

Figure 3.10 shows a typical cross section of the single aspect house design. This clearly shows how the roof level was lowered by sloping the edges of the first floor ceilings. This reduction in roof height allowed a closer block-to-block spacing thereby relieving the constraints on

* There would however have been a larger total area of wall in the single aspect design, and a longer floor perimeter, both of which would have increased the fabric loss of these houses relative to the dual aspect houses. This effect was not appreciated by the researchers at the design stage.



North Facade

Single aspect house plans

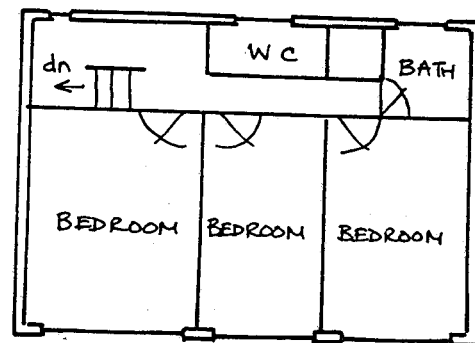
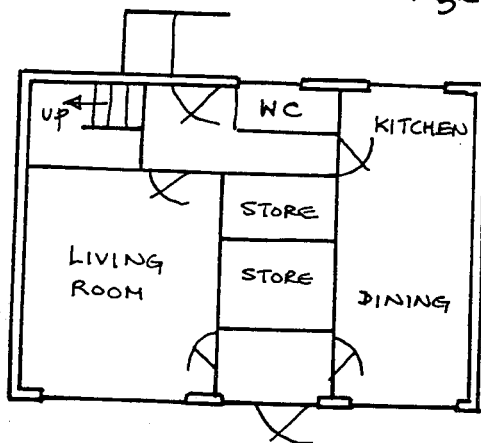
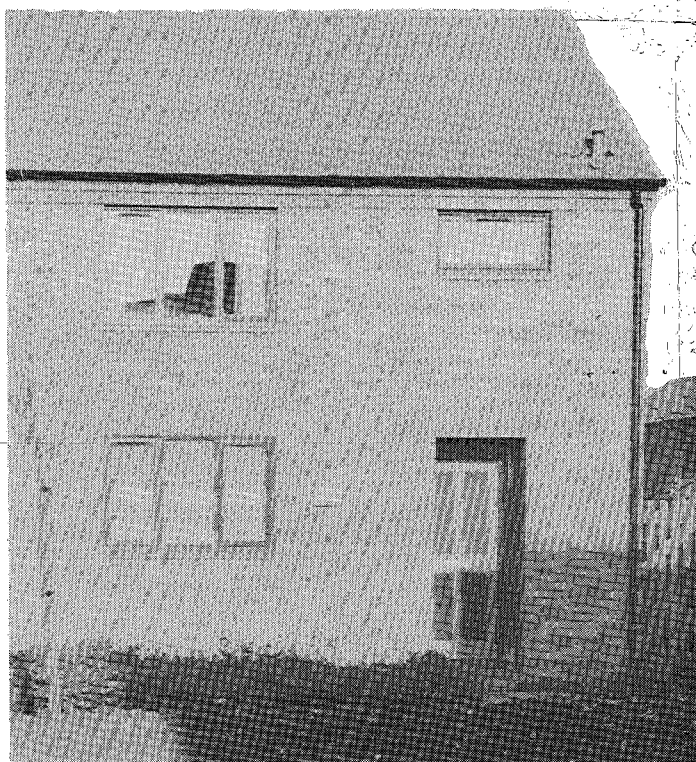


Figure 3.8

Single Aspect
Plans and Elevations

South Facade

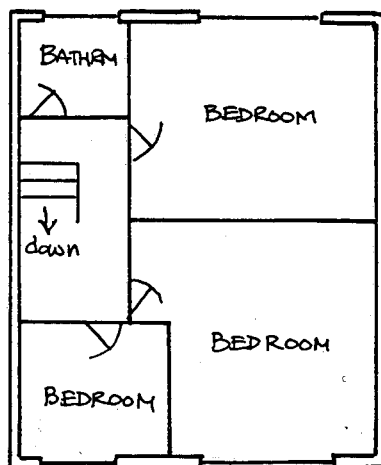
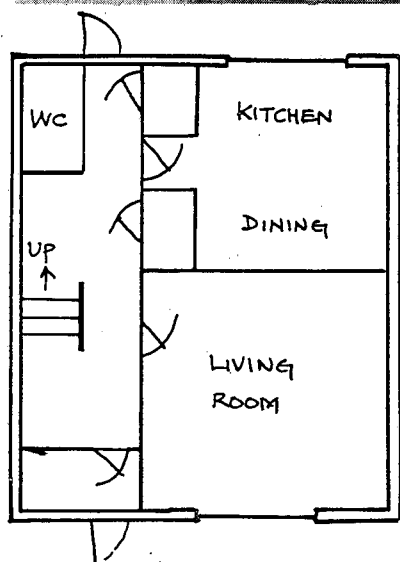




North Facade

Figure 3.9

Dual Aspect
Plans and Elevations



South Facade



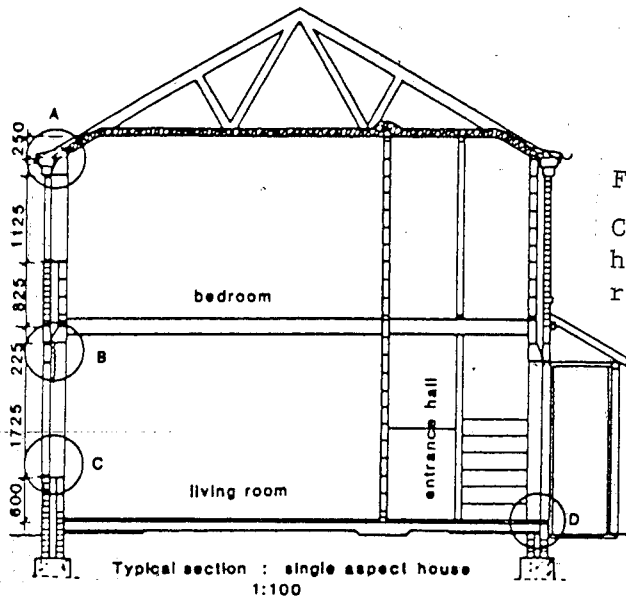


Figure 3.10

Cross-section of a single aspect house showing the lowering of the roofline to avoid overshadowing.

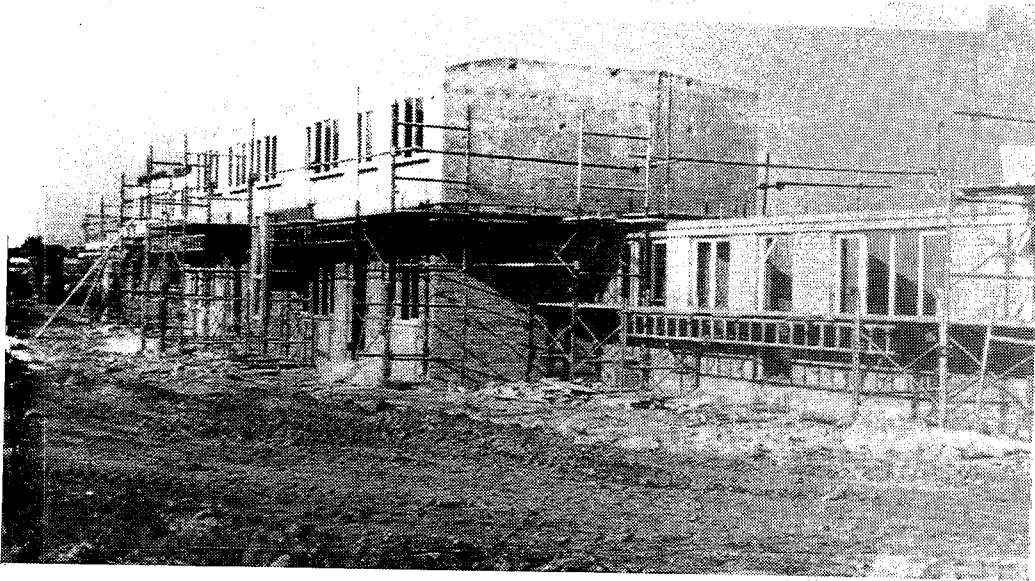
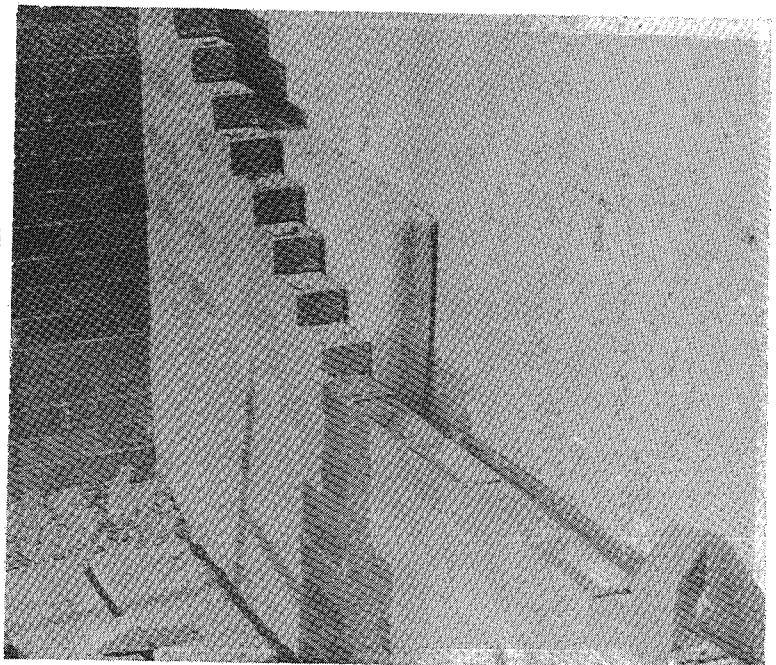


Figure 3.11

The Pennyland houses were built by John Mowlem Ltd. using their poured concrete construction method. The inner skin was cast a floor at a time with the insulation and brick outer skin being added afterwards.

Figure 3.12



housing density somewhat. However it should be noted that this reduction in roof height made it more difficult to install insulation in the eaves at the edge of the roof. This was a feature identified in the buildability study as one likely to cause condensation and damp in roof timbers, and this was indeed found in a later survey. Further plans of the houses, including drawings of details, are presented in Appendix 3.

Insulation standards

As indicated earlier the Pennyland estate is divided into two areas with different levels of insulation in each. The insulation standards are;

Area 1: Moderately insulated

Item:	U-value
80 mm mineral fibre loft insulation	0.41
50 mm mineral fibre slab insulation in cavity	0.60
single glazing fitted with draught seal	4.30
solid floor, no insulation	0.45-0.76

Area 2: Highly insulated

150 mm mineral fibre loft insulation	0.30
100 mm mineral fibre slab insulation in cavity	0.34
double glazing fitted with draught seals	2.50
25mm edge slab insulation on solid floor	0.34-0.56

From the calculations set out in Appendix 4 it is found that for a typical 5 person single aspect house these insulation levels give an overall fabric loss of 182W/K for area 1 and 127W/K for area 2. It is important to appreciate the significance of the word "typical" in the above statement. Due to the variation in overall house size, from 2-person (1 bedroom) to 7-person (4 bedroom) houses, and the variation in terracing, from detached to mid-terrace with eight distinct levels between these extremes, there is in fact a significant range of fabric heat loss values (100-140 W/K in area 2 and 140-210 W/K in area 1) on both areas of the estate. Histograms of the fabric loss values for both areas are shown in Figure 3.13

Part of the specification for the Pennyland houses was that they should be thermally massive, i.e. that the external and internal walls should have a high thermal capacity. Although the houses were designed for conventional blockwork the contractor chose to adopt a non-traditional form of construction, namely the Mowlem Quickbuild system. In this system the inner walls are concrete, cast in situ in two stages (to the first floor and then to roof level). The outer skin, of 103mm facing bricks, is

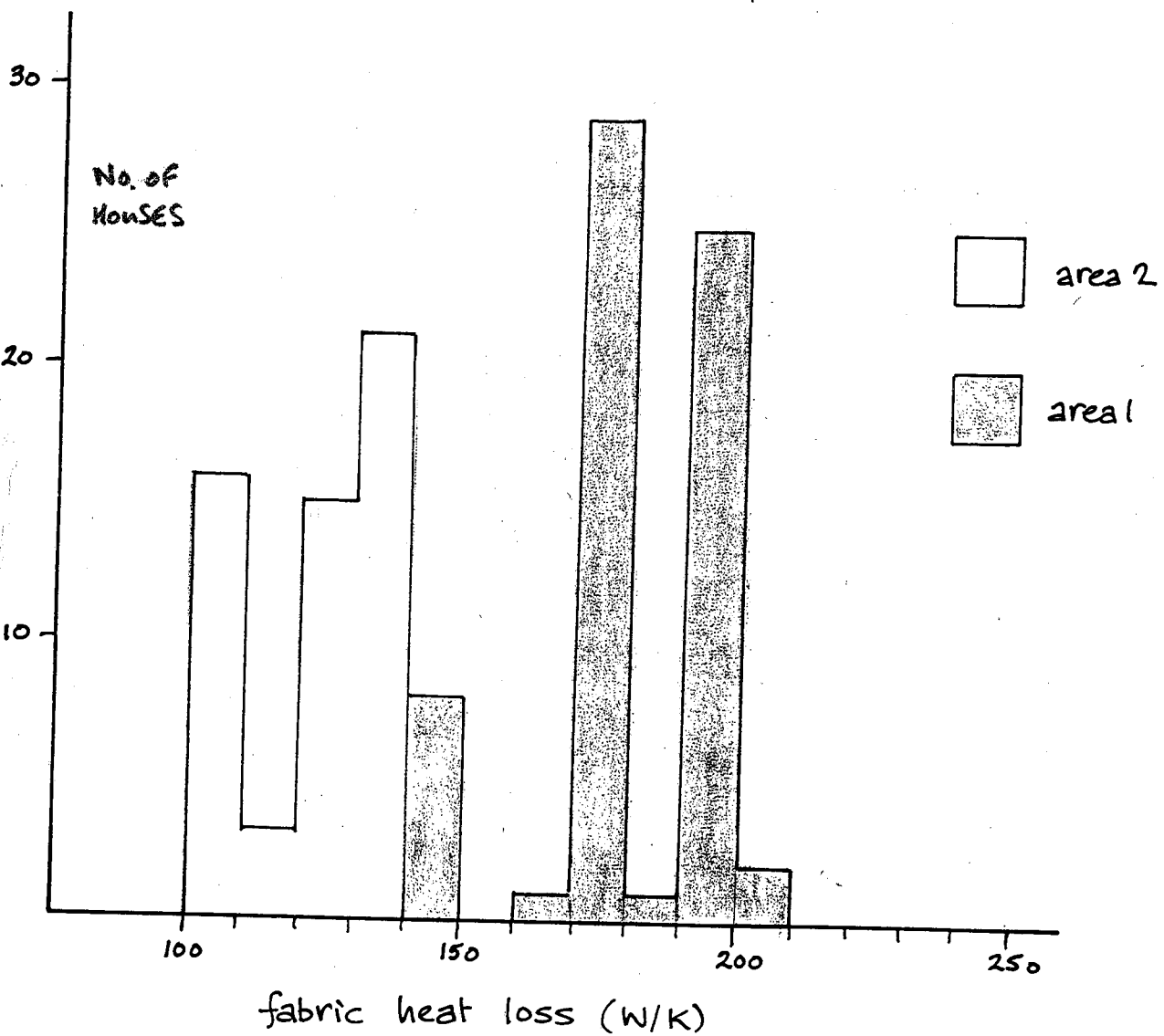


Figure 3.13 Illustrating the range of fabric losses for houses in areas 1 and 2 of Pennyland

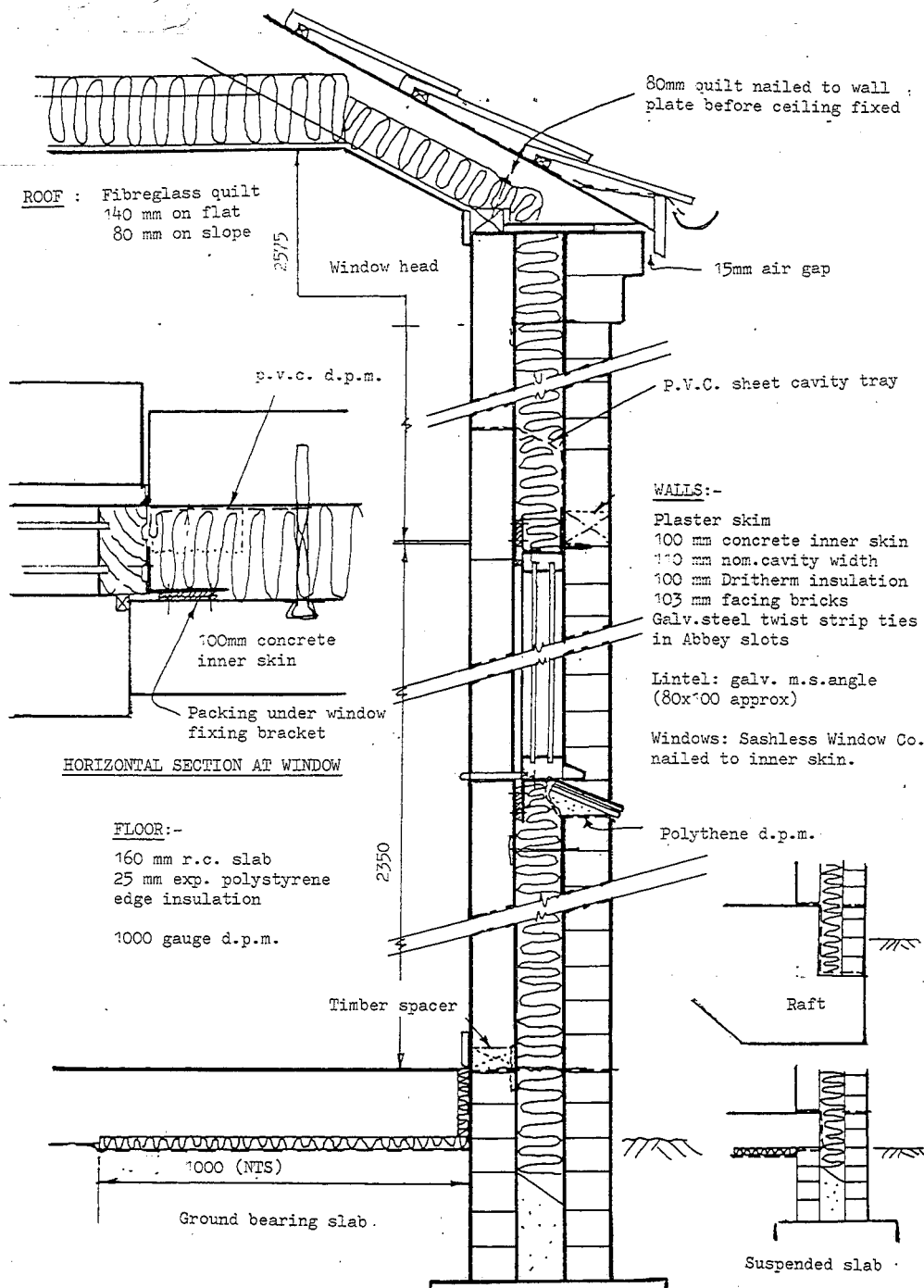


Figure 3.14 Construction details of a Pennyland Area 2 house. Area 1 houses are similar with thinner insulation and no floor insulation.

added later. On Pennyland 1 the cavity between inner and outer walls was nominally 63mm and on Pennyland 2 110mm. "Dritherm" glass fibre batts were built into these cavities. The construction sequence, which differed slightly between areas 1 and 2, is discussed further in section 4.2 (Buildability).

The roof structure was of conventional trussed rafters with reinforced bitumen felt and interlocking concrete tiles. The insulation was installed in two stages. The 80mm sloping sections were nailed to the wall plate between the rafters before completing the roof. The main flat section was insulated with glass fibre rolls laid between the joists after the roof was complete.

In area 2 an economical form of double glazing was used, Quebec 35 MkII from the Sashless Window Co.Ltd. In fact these double glazed windows cost no more than the conventional casement windows installed on area 1! Also in area 2 the reinforced concrete floor slab is insulated with 25mm expanded polystyrene around the edge (for details see drawings in Appendix 3).

Heating System

As will be made clear in the following sections, most of the analysis of energy consumption on the Pennyland houses has been concentrated on the 5-person (abbreviated 5P) houses since these form the largest group of similar house types. For this reason the description of the heating system focuses on the system installed in these houses. For other house sizes the boiler and radiator sizing is different, though the general standard of heating is the same.

The houses have partial central heating, there being radiators in the living room, kitchen/dining room, hallway and bathroom. There is anecdotal evidence that in some houses residents have installed radiators in bedrooms. The heat is supplied by a Corvec Miniflame II balanced flue gas boiler, which is mounted on the wall in the kitchen. Its nominal rating is 10.06 kW gas input, 8.2 kW water output. On this basis the full load efficiency quoted by the manufacturer is 82%, a figure consistent with studies carried out in this project (see section 5.2). The boiler has a very low thermal capacity; it holds 0.18 litres of water.

The boiler primaries (22mm pipe) are led to the upstairs airing cupboard which houses the boiler pump, diverter valve, hot water cylinder and, where fitted, the heat meters. None of the pipework is insulated. In the

Figure 3.15

The frameless sliding glass double glazing made by the Sashless Window Co. and used in Pennyland Area 2 and at Linford.

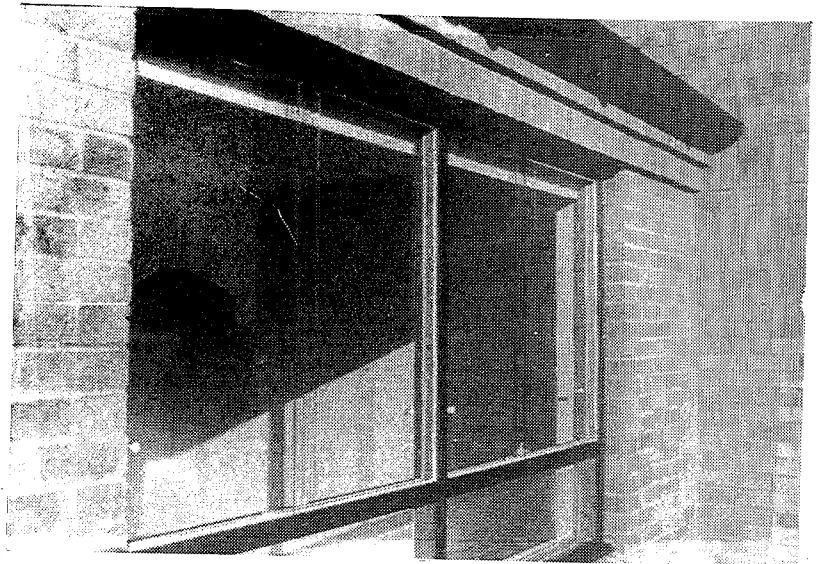


Figure 3.16

Concertina insulating window shutters fitted to some of the Pennyland Area 2 houses

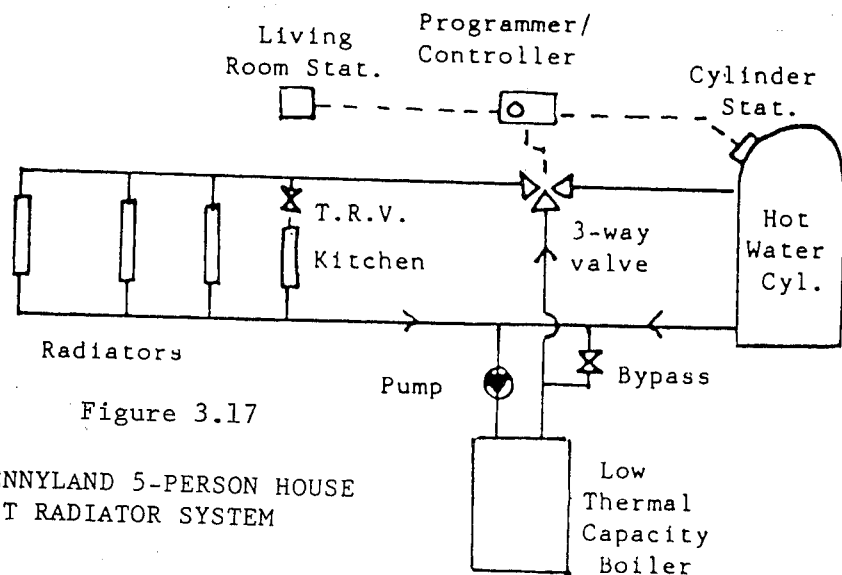


Figure 3.17

PENNYLAND 5-PERSON HOUSE
WET RADIATOR SYSTEM

dual aspect houses the length of the boiler primaries is 4m as opposed to 1.5m in the single aspect. The difference arises from the layout differences (see detailed drawings in appendix 3). The hot water cylinders are 144 litre copper cylinders insulated with fibre-glass jackets of 25 mm thickness. The heating systems in all the houses are controlled by a programmer on the kitchen wall, a room thermostat in the living room and a cylinder thermostat on the DHW tank. The programmer allows independent one or two period operation of space and water heating. The cylinder thermostat is a Drayton model CS1.

In general the uniformly high average house temperatures recorded as part of the monitoring indicate that the heating systems were adequately sized and that the occupants enjoyed a high level of thermal comfort. This is also confirmed by the results of the social survey.

Summary of House types

The following tables summarise the main characteristics of the houses on Pennyland area 1 and 2. Table 4 gives a summary of the characteristics of the 5P houses.

Table 2: House characteristics Pennyland area 1.

Orientation	Aspect	Terracing	Size	Number
East/west	dual	end	5	8
"	dual	mid-	5	1
South west	dual	end	5	2
"	dual	mid	5	2
South	dual	detached	2	1
"	"	"	5	2
"	"	end-	2	1
"	"	"	5	16
"	"	mid	5	6
South	single	end	2	1
"	single	"	3	4
"	"	"	5	11
"	"	"	6	4
"	"	"	7	2
"	"	mid-	2	6
"	"	"	3	2
"	"	"	5	18
"	"	"	6	5
"	"	"	7	2
TOTAL				94 houses

Breakdown:

5P dual aspect	37
2P dual aspect	2
5P single aspect	29
6 & 7P single aspect	13
2 & 3P single aspect	13

Table 3: House characteristics Pennyland area 2

Orientation	Aspect	Terracing	Size	Number
South-east	dual	end	5	3
„	„	mid	5	3
„	single	detached	3	1
„	„	end	5	8
„	„	„	7	1
„	„	mid	2	1
„	„	„	5	1
„	„	„	6	2
South-west	dual	end	2	1
„	„	mid	5	4
„	single	detached	3	1
„	„	end	3	1
„	„	„	5	3
„	„	mid	2	1
„	„	„	5	1
South	dual	detached	5	1
„	„	end	5	10
„	„	mid	5	11
„	single	end	2	1
„	„	„	3	4
„	„	„	5	7
„	„	„	6	5
„	„	„	7	3
„	„	mid	5	3
„	„	„	6	4
„	„	„	7	2
TOTAL				83 houses

Breakdown:

5P dual aspect	32
2P dual aspect	1
5P single aspect	23
6 & 7P single aspect	17
2 & 3P single aspect	10

Table 4: Summary of 5P house characteristics on Pennyland

AREA 1	SINGLE ASPECT				DUAL ASPECT		
	det	end-t	mid-t		det	end-t	mid-t
South	-	11	18		2	16	6
S-west	-	-	-		-	2	2
E-west	-	-	-		-	8	1
AREA 2							
South	-	7	3		1	10	11
S-west	-	3	1		-	-	4
S-east	-	8	1		-	3	3

It should be noted that the representation of terracing in the above tables has been simplified. As indicated earlier there are 8 identifiable levels of terracing, corresponding to staggered terraces and terraces involving one and two storey houses. Some of the combinations are indicated in Figure 3. 18

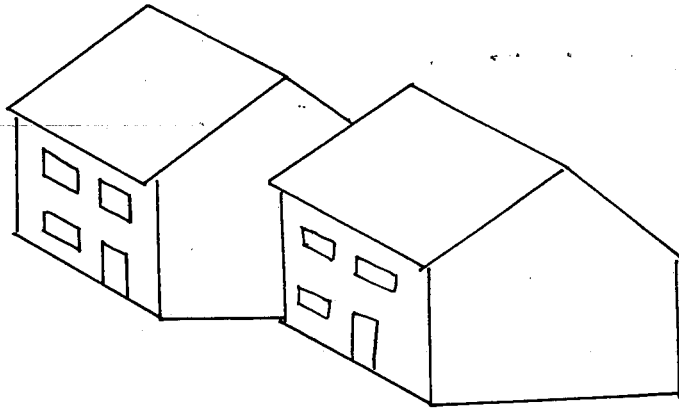
3.3. The control - Neath Hill

The Neath Hill estate was built in 1978/9, being thus incorporated into the Pennyland project retrospectively. The estate was laid out with a view to producing a village community with the houses in a series of mews courtyards. The mews were designed as tightly as possible with a minimum of 10m between single aspect houses. This means that some of the houses are heavily overshadowed. The estate has a high provision for car-parking with an average of 1.9 parking places per dwelling.

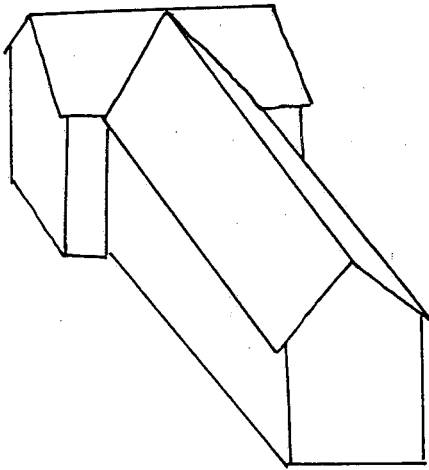
In the experiment the Neath Hill estate was used in two ways. First a group of 18 houses were selected as a control group for the solar experiment. These were insulated to the same nominal standard as Pennyland 1 by filling the 50mm cavity walls with urea-formaldehyde foam. This group was intensively monitored (see section 4.1). Later a second group of uninsulated houses was selected to act as a comparison for part of the insulation study. These houses were only monitored by examining quarterly gas bills.

The layout of the part of the estate containing the 18 better insulated houses is shown in Figure 3. 19 The orientation of these houses is as

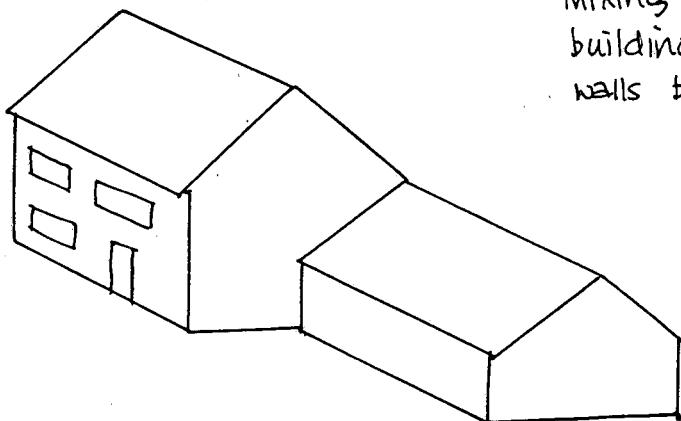
Figure 3.18. Illustrating different degrees of terracing



horizontal staggering leads to some end walls being half exposed.



mixing single and dual aspect houses in terraces leads to some end walls being three-quarters exposed



Mixing single and two storey buildings leads to some end walls being one quarter exposed

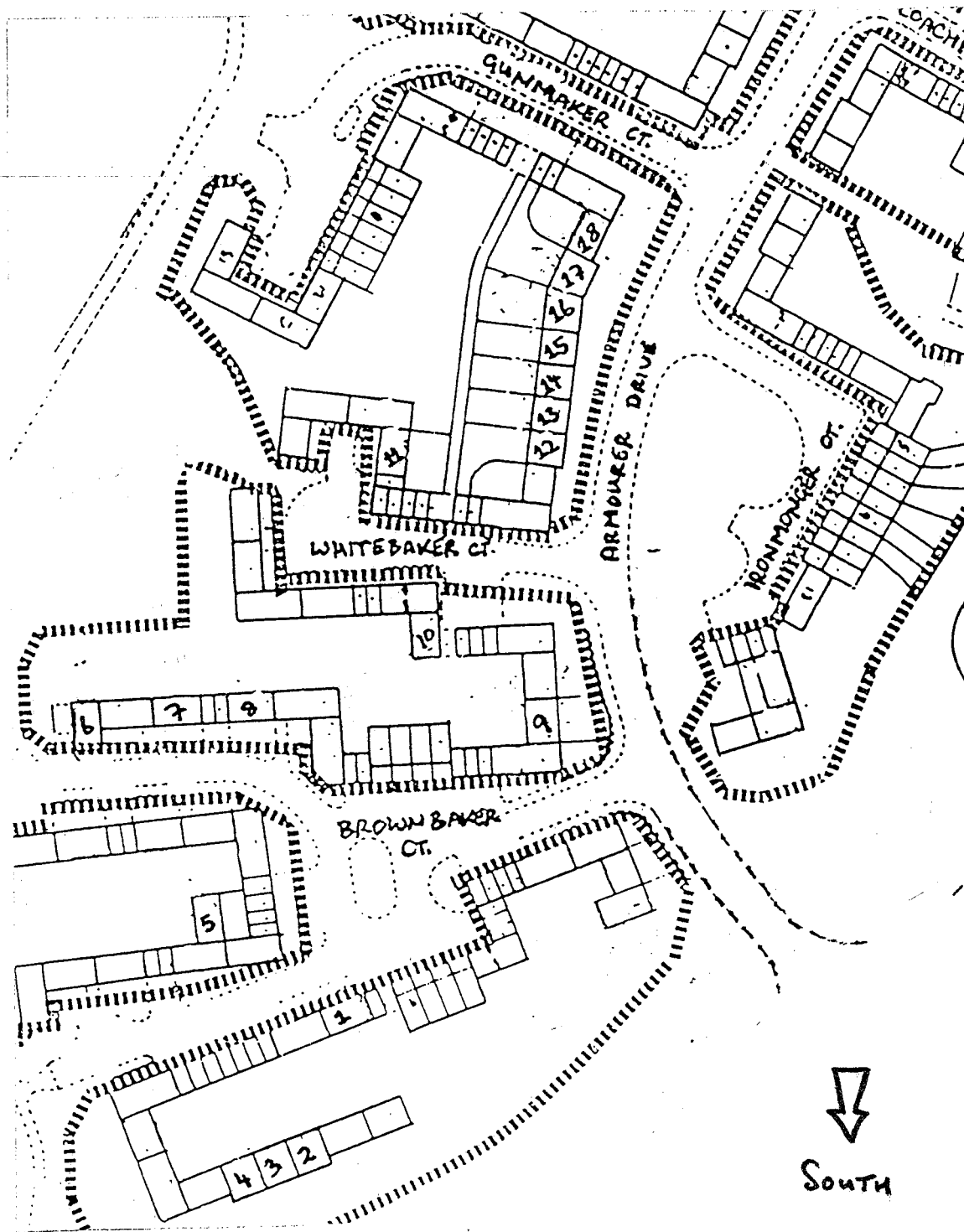


Figure 3.19

Location of the Neath Hill Insulated
Houses with Detailed Monitoring

follows:-

direction	house id numbers
south	1,2,3,4
north	7,8
east	5,6,12-18
west	10,11

All of the monitored houses on Neath Hill are of the 5P size (3- bedroom). They are of two basic types, shallow and deep plan - in some respects similar to the single and dual aspect houses of Pennyland. The house plans are illustrated in Figure 3.20. Two of the houses are "splayed" in which one of the end walls makes an angle of 100° with the front wall of the house, enabling a 20° bend to be put in one of the terraces.

The detailed drawings of the Neath Hill houses are presented in Appendix 3 and the fabric loss data in Appendix 4. The glazing is concentrated on one face of the house. For the shallow plan houses there is 11.7 sq.m on the back and 6.5 sq.m on the front. For the deep plan houses the back has 9 sq.m and front 6.5 sq.m. This means that the shallow plan houses on Neath Hill are potentially nearly as "solar" as the single aspect houses on Pennyland.

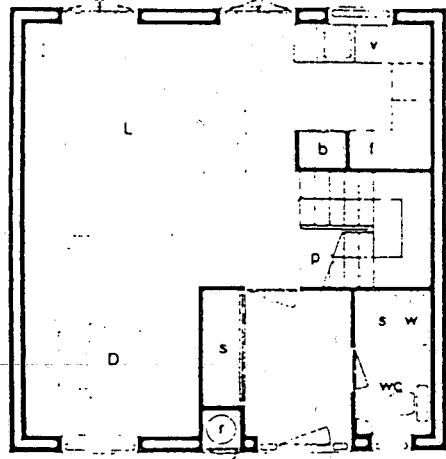
The Neath Hill houses were built to the 1976 Building Regulations. They all have brick/lightweight block, 50mm cavity walls. Internal partitions are mostly plasterboard on studs. Ground floors are concrete slab with no insulation. Roof insulation is 50mm. In 1980 the external walls of the 18 monitored houses were insulated with urea-formaldehyde foam. The average fabric heat loss of the uninsulated houses is 204 W/K and for the better insulated group 168 W/K. For further details of the fabric loss and the range for the house types see Appendix 4.

There are two standards of heating on the Neath Hill estate, partial and full central heating. In the monitored sample houses 2,3,4,10,16 and 17 have full central heating, the rest have no radiators upstairs. Detailed layouts of the boiler and radiators are included in the house plans in Appendix 3. The boilers used are Thorn Olympic 38/50 high thermal capacity, conventionally flued. The boilers were of three different ratings, 11.1, 12.9 or 14.7 kW and the continuous operating efficiencies were quoted as being 73-75%. The boiler has a water capacity of 4.55 litres.

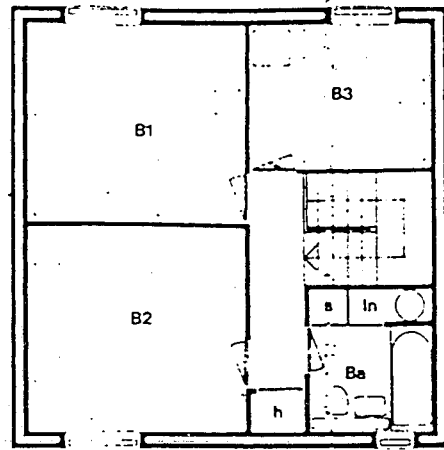
The boiler is sited upstairs in a cupboard on an outside wall. Air supply is nominally through a duct, formed by a plasterboard partition in the boiler cupboard, that leads to the attic. The cupboard door is not draughtproofed and it is possible that some of the air supply is drawn

from the house. The boiler cupboard houses the pump, diverter valve and heat meter(s).

The boiler primaries are 22mm and there is a 22mm pipe to the main space heating circuit. The DHW tank has a capacity of 120 litres insulated with about 15mm sprayed polyurethane foam. The pipe run to the cylinder is about 1.5m in the wide frontage houses and 4.5m in the narrow frontage; none of the pipes is insulated. The heating systems are controlled by a programmer integral with the boiler, a room thermostat and a cylinder stat. The programmer can be set for HW only or heating plus HW for two periods a day. The cylinder thermostat is made by Satchwell.

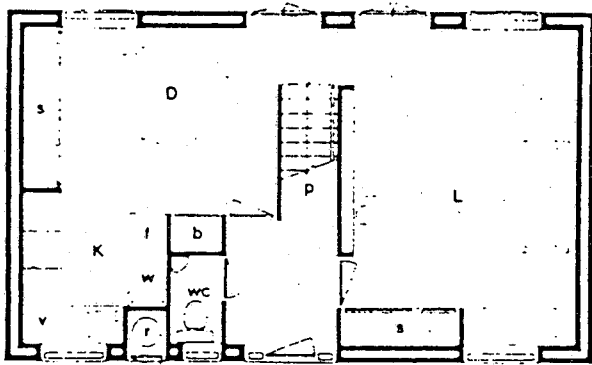


↑
ground floor

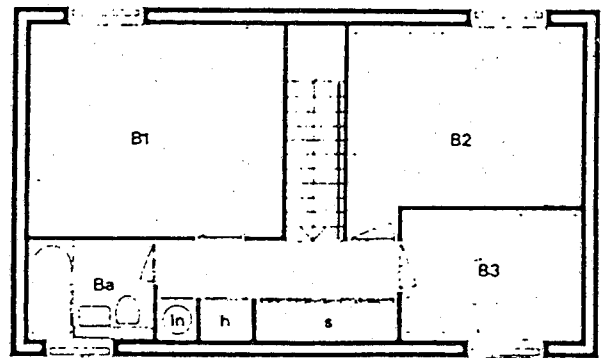


first floor

DEEP PLAN DUAL ASPECT



↑
ground floor



first floor

SHALLOW PLAN DUAL ASPECT

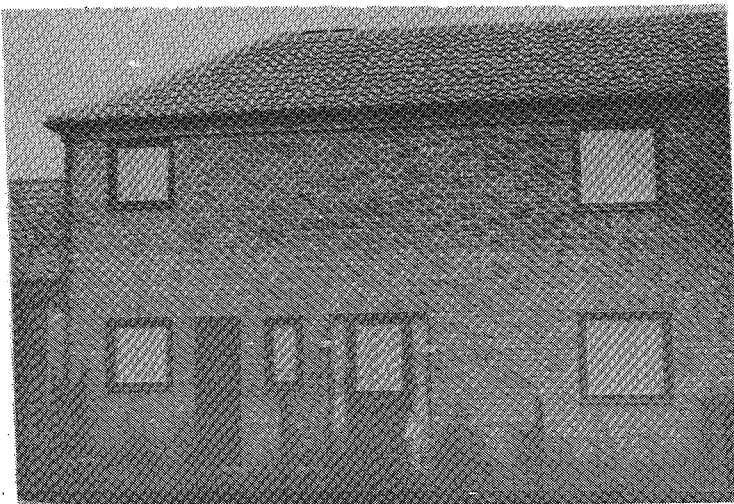


Figure 3.20

NEATH HILL HOUSES

Typical Facade (shallow plan)

CHAPTER 4

MONITORING

CONTENTS

- 4.1 Introduction
 - 4.2 Buildability
 - 4.3 Temperature & Energy Measurement
 - 4.4 Data Collection, Cleaning & Quality
 - 4.5 Social Survey
 - 4.6 Pressure Tests
 - 4.7 Thermographic Survey
 - 4.8 Weather Data
-

This chapter describes the various ways in which the Pennyland project houses have been monitored. This includes inspection of the construction, condensation studies, fuel use and temperature measurement, a thermographic survey, air leakage tests and a social survey.

4. MONITORING

4.1. Introduction

This section of the report is concerned with all the different ways in which the houses at Pennyland and Neath Hill have been monitored. Although the main experiment was concerned with evaluating the changes in fuel use associated with better insulation and passive solar measures, it was also very important that the houses were monitored for ease of construction, social acceptability and other performance criteria such as condensation problems. Clearly it is no use having a low energy house that cannot be built, is awful to live in, and falls down after a few years!

The full range of monitoring activities discussed in this chapter are as follows:-

- A. Buildability study. This was carried out by the Building Research Establishment. The full report of their findings is published by them (ref. 4.1). The main findings are summarised in section 4.2.
- B. Condensation study. This was a limited survey of the test house at Linford and four houses at Pennyland. The results are discussed at the end of the buildability section, since they are directly related to that previous work.
- C. Temperature and energy use data collection and data cleaning. Section 4.3 explains the underlying monitoring strategy and data collection system. Section 4.4 describes the data handling and the need for data 'cleaning' (removing equipment errors and periods when the houses have been empty from the data set). The computer database is further described in Appendix 6 and the cleaning process in Appendix 9.
- D. Social Survey. This was carried out by Milton Keynes Development Corporation. The full report is available from them and a summary of the main findings is presented in section 4.5.
- E. Pressure tests. Houses at Linford, Pennyland and Neath Hill were pressurised with large fans to check air leakage. The test results can be used to estimate infiltration rates, and hence ventilation losses. The results are summarised in section 4.6. and the methods used discussed in Appendix 7.
- F. Thermographic Survey. This was a limited study using an infra-red camera to examine buildings at Linford, Pennyland and Neath Hill. The results are shown in section 4.7.
- G. Weather Data. The Linford project incorporated a weather station in the garden of the test house. This was used to monitor the main weather variables. The Linford site is within half a mile of the Pennyland estate. The main weather data is summarised in section 4.8 and presented in more detail in Appendix 8.

In addition to these specific monitoring activities, there was also a continuous process of exchange between the work done on the Linford and Pennyland projects. This included steady improvements in the use of the NBSLD computer model used for the original design predictions. This is discussed further in chapter 6.

4.2. Buildability

During the construction period in 1979/80, the problems of 'buildability' were assessed by the Construction Methods Section of the Building Process Division of the BRE. An interim report was written in January 1980 (N(C) 1/80), and a final one in December 1980 (N(C) 43/80), which is available as a companion volume to this report. A further BRE note (N77/81) compared observations at Pennyland, Linford and two other UK schemes using wide cavity wall constructions, in Manchester and Wakefield. This note (also available as a companion volume) also included some relevant Danish design recommendations; cavities of 100-125mm have been common practice in Denmark for some decades.

The conclusions of the Pennyland study are summarised briefly here. They concern:

- i) the floor slab
- ii) the external walls
- iii) the roof.

The inclusion of insulation around the floor slab did not seem to present any difficulties. Slabs of three different designs were used at Pennyland, floating slab, suspended slab, and raft foundation. The cost of including the insulation was estimated to be the material cost and the cost of laying it; the costs of other building operations were not apparently affected. The only departure from design occurred at the edges of the floating slabs, where the concrete could form a lip over the vertical strips of insulation (see figure 3.14). This cold bridge was not thought likely to seriously reduce the effect of the insulation, which is likely to have been small anyway.

The inclusion of the insulation batts during construction of the external walls did not present any major problems, but some minor difficulties were noted. In area 1 the original intent was to secure the 50mm batts using the wall ties, but this was found to be unworkable; instead they were attached to the inner leaf of the walls using masonry nails, before laying the outer brickwork. This made it easy to inspect for gaps in the insulation. On the other hand the nails provide possible additional paths for rain water to cross the cavity, and additional cold bridges. In area 2 the 100mm batts were slotted into the cavity when three courses of bricks had been laid above the row of batts underneath. This made it difficult to inspect for gaps and allowed mortar 'snots' to be sandwiched between the rows of batts.

The method of wall construction and setting out led to undesirable variations in the cavity width: in area 1 the cavity tended to be larger than designed, with little apparent effect on the insulation but some incomplete embedment of wall ties; in area 2 the cavity tended to be

smaller than designed, the batts being compressed slightly, but the wall ties being well embedded. The door and window detailing in general coped well with the varying cavity width, except for over-compression of insulation behind some lintels. The cost of the wall insulation again seemed to be limited to the direct labour and material costs, and did not interfere with other site operations.

The roof insulation was carried out by a sub-contractor, except for the sloping parts which were fitted by the main contractor before the roof was completed; the combined operation was not always satisfactory at this detail, incomplete insulation and/or blocked ventilation gaps being noted. The main roof insulation was carried out after the plumbing. Apart from this there was no interference with other building operations.

The buildability study had intended to include an assessment of the extra labour costs associated with the additional insulation. In fact this was not done because the estimated differences in labour costs were of the order of a tenth of the known variation in labour costs for building identical houses.

Condensation

One of the risks associated with increasing the insulation level in a building, without installing a vapour barrier, is that condensation will occur within parts of the building fabric giving rise to damp patches, mould growth and even rot. The condensation occurs because the dew-point (the temperature at which the air releases water vapour) is very likely to occur within the fabric of a well insulated house (whereas it normally falls outside the fabric for poorly insulated houses). The areas most at risk are the roof timbers and the insulation in the wall cavities.

In March 1982 some measurements were carried out of condensation in four Pennyland houses (and the Linford test house). These were not exhaustive, and were intended to provide a basis for a more comprehensive condensation monitoring scheme. As the results from the pilot study were in general favourable it was not thought necessary to carry out further monitoring. The report on the pilot study is available as an ERG working paper; its main findings are summarised here.

A protimeter (a conductivity probe) was used to measure roof timber and cavity wall moisture content. A proposal to use a thermohydrograph to measure kitchen humidity levels was considered, but not pursued.

The roof timber measurements made best use of the instrument for its intended purpose, determining whether the moisture content of timbers, both on the surface and 12mm beneath the surface, was below that likely to cause rot (22% moisture by weight). Initial measurements at the Great Linford test house showed safe levels in the range 11-15%. It must however be remembered that this house was never normally occupied during this period, and had essentially no sources of internal moisture. At Pennyland a series of five measurements were made on roof trusses (see figure 4.1) in 4 occupied houses. The measurement points chosen were:

- 1) the side of the rafter as near to the sarking as possible.
- 2) the underside of the rafter.
- 3) an intermediate truss member.
- 4) the top surface of a joist.
- 5) the side of a joist. This measurement required the insulation to be pulled away from the joist at this point.

Each position was tested on the surface and 12mm deep into the timber. The complete pattern was repeated three times in each attic, including once over the bathroom. All figures were in the range 10-18% indicating safe levels of moisture.

However, during these measurements damp staining was noticed in one house on the sloping ceiling of all south facing bedrooms. Although the timber readings, and the rather more qualitative readings of the moisture levels in the plaster were all satisfactory, it was clear from the householder that damp had been severe in the January of 1982. It was then observed that in the case of this house the insulation in the sloping section of the roof had been pushed into the eaves from the attic so as to touch the sarking and block the flow of air from the soffits. This problem had been predicted by the buildability study as likely to arise due to the method of insulating this part of the roof (see figure 4.2).

The measurement of cavity wall moisture presented more of a problem, as the protimeter needs recalibration for materials other than timber. Readings were obtained using the relative scale. In the Linford test house readings were taken on two exposed walls, and two walls sheltered by the garage; in brick and in mortar; using drilled holes to compare the outside surface and deep within the outer leaf, and the outside surface and inner plaster surface of the inner leaf of the wall. The interpretation of these results remains uncertain. In the Pennyland houses it was felt that drilling holes in the walls was unacceptable, and measurements were limited to observations at the inner surface of the inner leaf of the wall (this was not plastered) near the kitchen sink and in one other place. All the readings were below 40% on the relative scale which is said to represent an "air dry" condition.

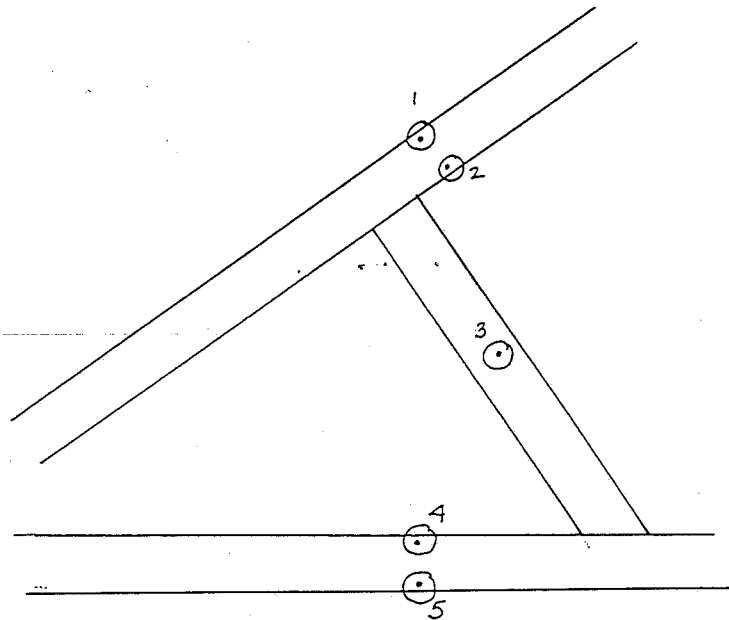


Figure 4.1 Indicating the condensation test sites in the roof trusses

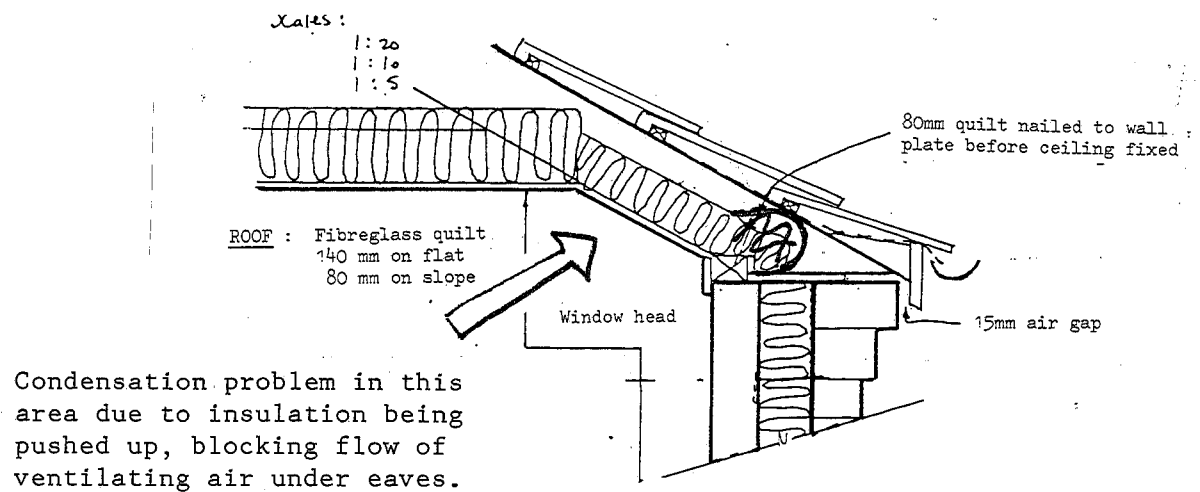


Figure 4.2 Condensation problem found in one house.

Conclusions on Buildability

It is clear from the buildability study that the better insulated houses on Pennyland do not seem to present any difficulties in building. Furthermore the condensation study indicated that the higher level of insulation had not led to any significant increase in moisture levels in the roof timbers. The exception to this is the evidence of condensation in the sloping part of the roof in one house, caused by the difficulty of installing insulation at this point. This is not an effect of the extra insulation (there was no difference between the area 1 and 2 houses at this point), but an interaction of the solar design constraints with the presence of any insulation at this point. Further comments on condensation will be found in the digest of the social survey in section 4.5.

4.3 Temperature and Energy Measurement

The broad outline of the modelling strategy has already been set out in sections 2.2 and 2.3. There it was shown how the Pennyland experiment offered a number of different comparison groups, some involving differences in insulation levels and some differences in passive solar features (and some both). It was also pointed out that it was expected that the magnitude of the differences in fuel use in the solar and non-solar houses was significantly less than the variance of the raw fuel consumption data, indicating that it was necessary to measure additional variables so as to reduce the variance.

Although it seemed possible to estimate the energy savings due to the insulation measures by simple comparisons of the annual fuel consumptions of the different groups, it was clear from the outset that this would not be adequate to resolve the solar differences. The measurement of actual space heating energy rather than gas consumption would give better results and taking internal temperatures into account would improve matters further. It did seem, though, that these extra measurements, involving a considerable amount of monitoring effort, would still only be equivalent to a doubling of the sample sizes for the cruder comparisons. This still did not seem good enough.

The approach was therefore to monitor sufficient parameters to attempt some kind of 'house characterisation', to assess the energy response of each house type to outside air and solar radiation. The aim was to build up an energy balance on a weekly basis:-

$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

where Q = weekly space heating energy

K = free heat gains from cooking, lights, etc.

$\sum U.A$ = house fabric heat loss

C_v = average house ventilation rate (assumed constant)

ΔT = weekly average house inside-outside temperature difference

R = equivalent house 'solar aperture' or 'recuperation factor'

S = weekly solar radiation on the south-facing vertical surface

This method had been suggested by the U.S. Solar Energy Research Institute (S.E.R.I.) (ref. 1) but lacking any previous published results, it was not possible to tell how well the method might work. The aim was to extract values of $\sum U.A + C_v$ and R for the separate house types which would confirm how well the insulation was working and whether one type was more 'solar' than another.

The experimental design therefore involved the choice and development of a simple package of instrumentation to carry out this task without disturbing the house occupants. This package was designed around

weekly meter readings of gas and electricity meters but with some extra instrumentation added:-

1. An extra gas meter to measure cooking gas consumption
2. A heat meter in the central heating to measure actual space heating consumption
3. In some houses another heat meter for water heating energy
4. A specially developed 'Differential Temperature Integrator' to measure the house average ΔT .

4.3.1. Equipment

Gas Meters

These have been of a conventional type, which are specified by British Standard 4161 to be accurate to within 2% over flow rates from 4.2 to 212 cubic feet per hour (1.3 to 64 kW), and to have a minimum detectable flow of about 150 W. This is only about equal to the pilot light of the boilers installed at Pennyland.

Electricity Meters

These were of the normal revolving disc variety and are supposed to be 1% accurate.

Heat Meters

Heat meters did not have a very good reputation for accuracy in 1977 and the variety chosen, manufactured by Kamstrup Metro of Denmark with a Brunata flow meter had just been introduced.

They consist of several components:-

1. A brass body, screwed into the central heating pipework.
2. A plastic turbine measuring the flow of water in the pipe.
3. A pair of nickel resistance thermometers mounted in brass pockets measuring the temperatures in the flow and return pipes.
4. An electronic integrating head, containing a detector counting the rotations of the turbine and electronics to multiply by the temperature difference between the two temperature sensors. The resulting flow and energy readings are recorded on electromechanical counters.
5. A remote readout for the energy flow, located in the house meter cupboard alongside the other meters.

Access was required to the heat meter body roughly every six months to replace the battery powering the electronics.

A random sample of heat meters were calibrated in the laboratory at the end of the monitoring period, and were found to be over-reading by about 9%, though with wide variations between samples. This may be compared with the manufacturer's quoted accuracy of $\pm 5\%$ on each temperature and on the flow rate, giving an overall error of about $\pm 10\%$.

The heat meter components and installation are shown in figures 4.3-5.

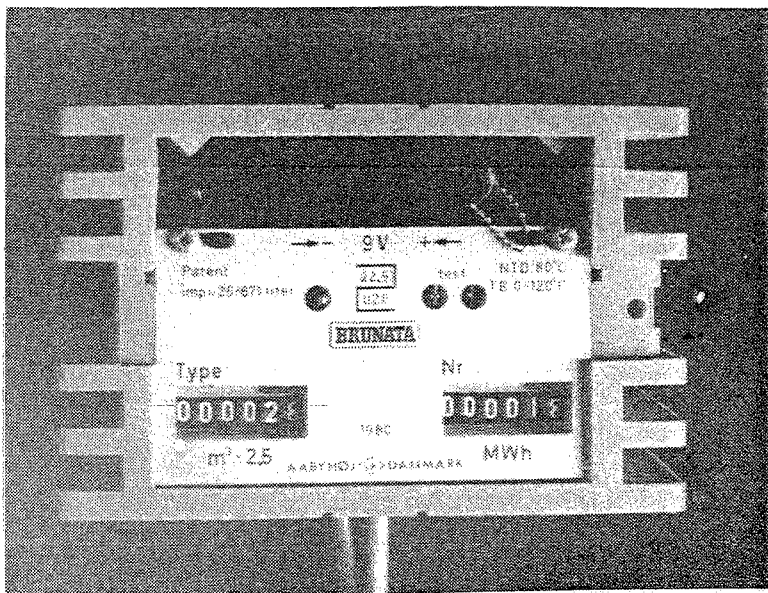


Figure 4.3

Heat meter integrating head

Figure 4.4

Turbine flow meter and water filter.

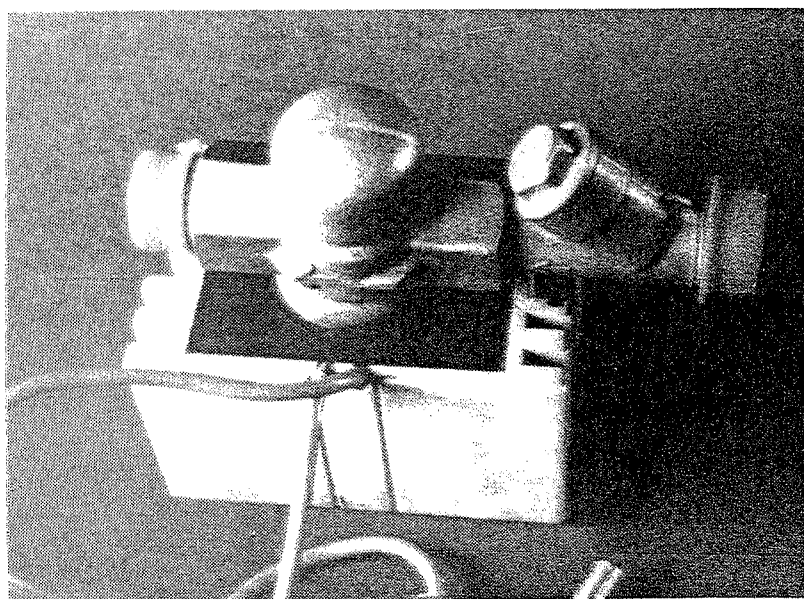
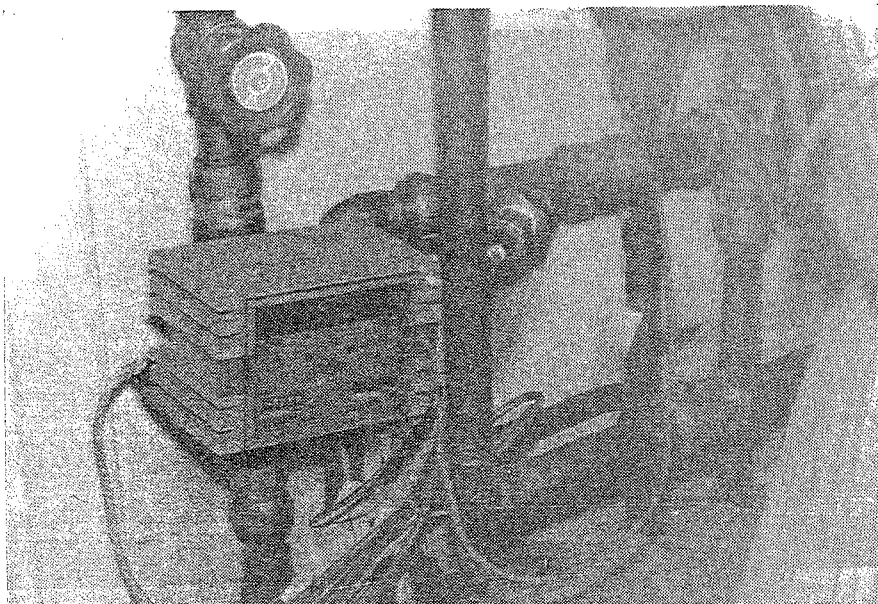


Figure 4.5

Meter installed in heating system



Differential Temperature Integrator

This is a kind of house temperature meter and was specifically developed for the project and manufactured by the Open University Electronics Department. This recorded the temperature in three rooms of the house, living room, kitchen, and one bedroom, indicating the cumulative difference between each of the sensors and an external sensor, hence the name 'Differential Temperature Integrator' or D.T.I. This can be thought of as an attempt to record real degree-days for each house.

The device measured ΔT rather than average internal temperature because the main aim was to produce an accurate house energy balance. Absolute internal temperatures could always be worked out afterwards from external temperatures measured elsewhere (such as the Linford weather station). Their absolute accuracy for comparison purposes was not important, as long as differences between groups were accurate. This required that all the individual house external temperature sensors should ideally read the same temperature. Alas, this does not seem likely to have happened in practice.

Measuring ΔT has allowed houses to be monitored in isolation (such as one at Beanhill) and meant that the characterisation study could have been carried out even if the Linford project had not materialised (it had been cancelled at least five times by 1980).

The choice of only monitoring three internal temperatures was seen as a compromise between accurately determining an 'average' house internal temperature and the extra expense of designing an instrument to cope with many temperatures, plus the problems of installing sensors.

The sensors used were platinum resistance thermometers bought pre-calibrated to $\pm 0.3^\circ\text{C}$. This basically limits the D.T.I. performance to an accuracy of $\pm 8\%$ at a ΔT of 10°C . Sensors could have been bought to a higher tolerance but it was not thought worth the extra expense.

Temperature sensors were mounted either in a small 'cigarette holder' mount, projecting about 75 mm from the wall surface, or in conventional wall-mounted thermostat housings used for central heating sensors.

In addition to measuring cumulative ΔT 's the D.T.I.'s could sample instantaneous internal temperatures. This was intended to allow samples to be taken of evening living room temperatures without having to enter the house. In the event this feature was only used for checking sensors and monitoring peak summer temperatures.

Sampling Period

All of the relevant measured data was available for reading in the house meter cupboard outside the house and could be read at any time without disturbing the occupants (see schematic figure 4.7).

The meters were all read once a week for the houses with detailed monitoring. It would perhaps, in retrospect have been better to read the meters about once every three days, though it took the meter reader one whole day to tour the estates. Also, the limited resolution of the heat meters (10 kWh was the minimum unit clocked up) would have created a problem.

The statistical problems of daily vs. weekly monitoring have been investigated more thoroughly in the Linford project and readers are referred to the Rapid Thermal Calibration report for more details.



Figure 4.6 The D.T.I. house temperature meter specially developed for the project.

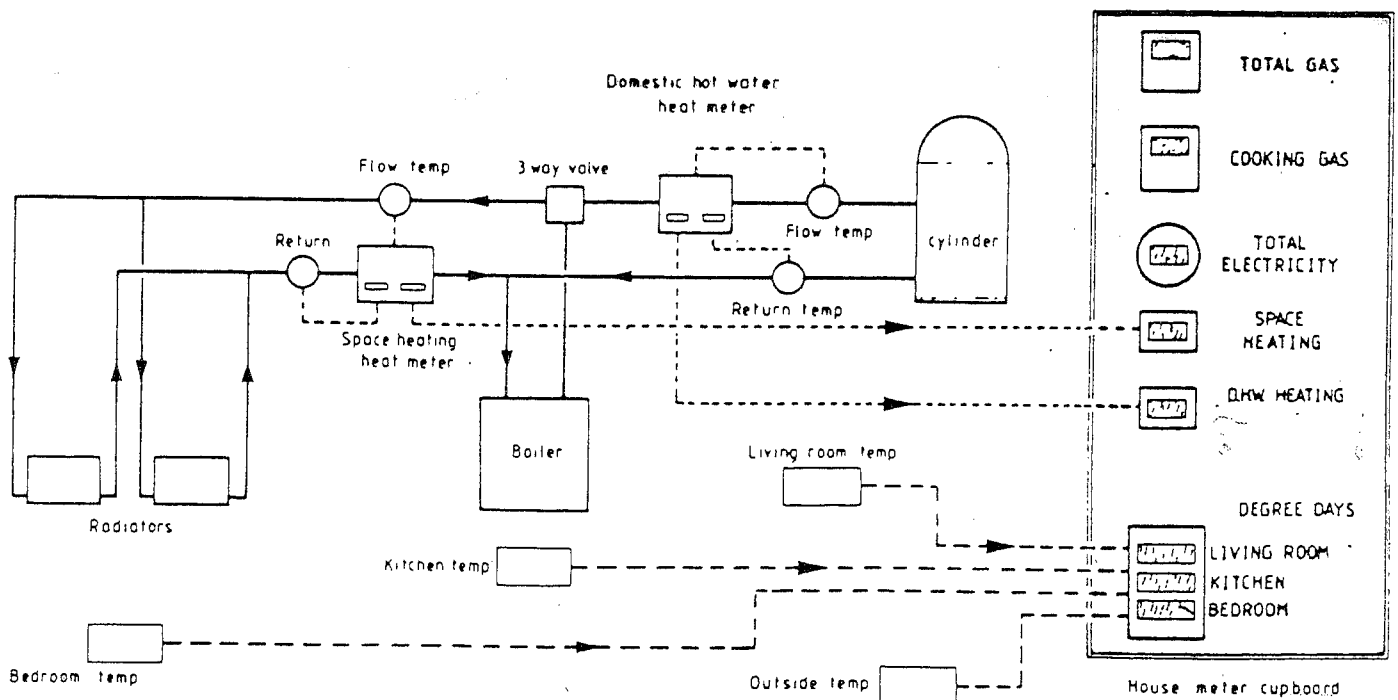


Figure 4.7 Overall Monitoring System Schematic (D.H.W. measurement in some houses only).

4.3.2. Deployment

The houses at Pennyland and Neath Hill were monitored essentially to four different levels, though the first level can hardly be called monitoring at all:-

Level 0 - Quarterly gas and electricity consumptions. This level covered all the Pennyland houses, the Neath Hill insulated group and 20 uninsulated Neath Hill houses. These consumptions were compared with figures from other Milton Keynes estates, gathered as part of the design study.

Level 1 - Monthly measurement of gas and electricity meters. This was done for all the Pennyland houses and for the Neath Hill insulated houses. This is about the minimum level that can be meaningfully analysed. The data was gathered largely 'for the record' and has been incorporated into the 'Better Insulated House' database.

Level 2 - Weekly measurements of gas and electricity consumption; second gas meter to record gas consumed in cooking, heat meter to record space heating output from the boiler and internal temperature measurements. This level of monitoring was applied to;

- (i) the 18 better insulated houses on Neath Hill,
- (ii) 20 dual aspect and 19 single aspect 5P houses in area 1 at Pennyland
- (iii) 19 5P houses in area 2 at Pennyland

As mentioned above, the primary aim was the 'characterisation' of the houses with a view to extracting the solar differences.

Level 3 - All the level 2 measurements plus a second heat meter to measure the heat supplied to the hot water cylinder. This enabled the total boiler heat output to be measured.

This was carried out on:-

- (i) all of the intensively monitored houses in Area 2.
It was realised that incidental gains would provide a considerable proportion of the heating demand in these houses, hence a greater need to understand all the energy flows in the house.
- (ii) 5 of the Neath Hill insulated houses. This was done after the discovery of the large energy consumption differences between Neath Hill and Pennyland Area 1 and was done to allow the Neath Hill boiler efficiency to be worked out.

The three main levels of monitoring are shown on Sankey diagrams in figures 4.2 - 4.5. These show how progressively less and less is left to be deduced as the level of monitoring intensity is increased.

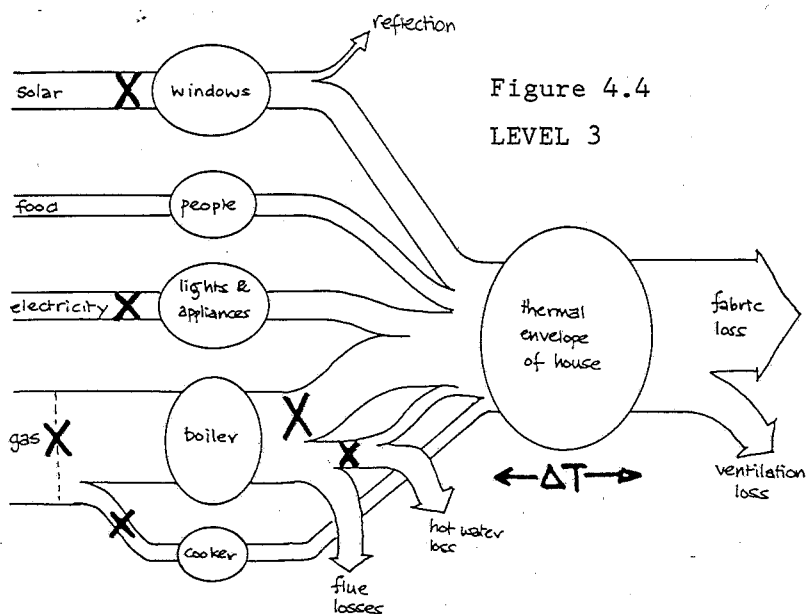
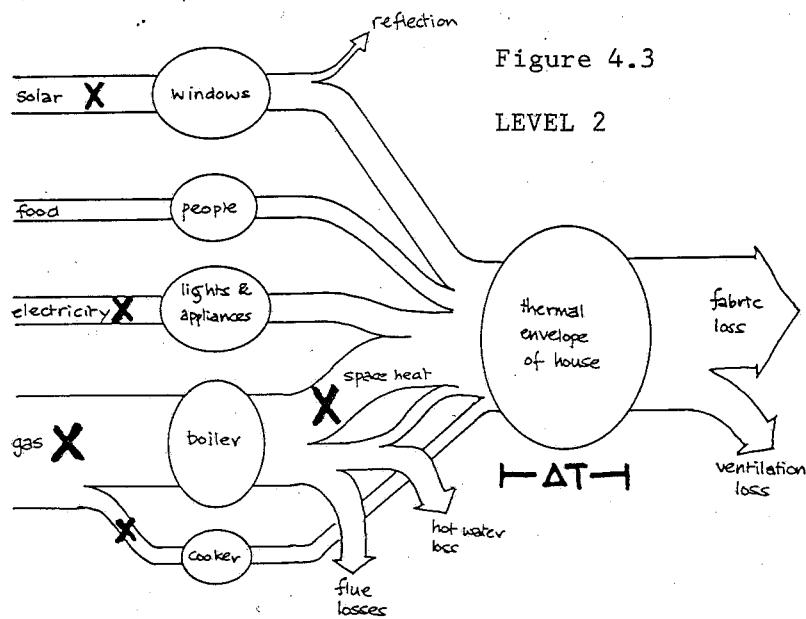
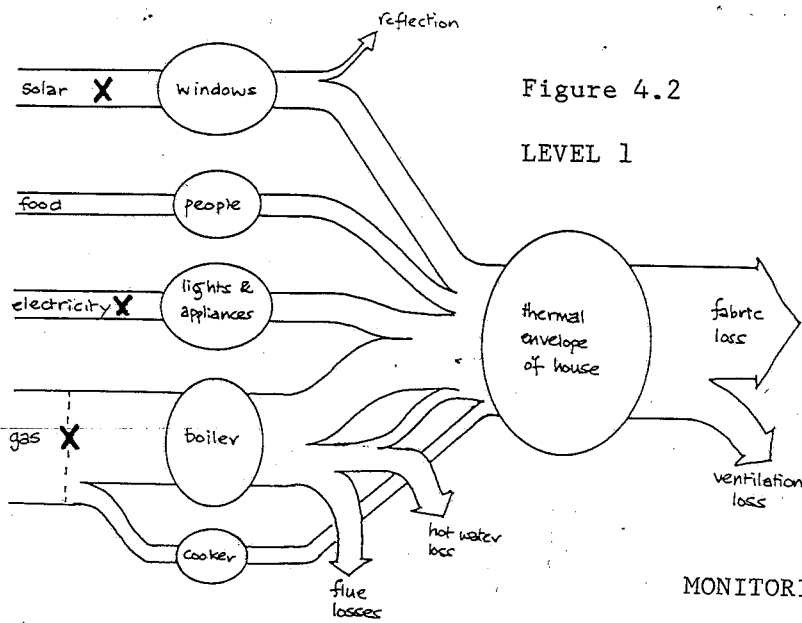


Figure 4.5 illustrates the relationship between the levels of monitoring and the comparisons to be made between groups of houses.

The Linford occupied houses were monitored to level 3 but with more internal temperature sensors and data recorded at 15 minute intervals rather than weekly averages.

On balance, the Pennyland monitoring package has given quite good value for money, the equipment costs working out at about £600/house at 1980 prices:-

Table 4.1 Monitoring Equipment Costs

	£	
Extra gas meter	30	
D.T.I., sensors and readout	240	
Heat Meter	120	
(Second heat meter for level 3)		(120)
Installation Cost	150	
	<hr/>	<hr/>
TOTAL	550	(670)

The more intensive Linford monitoring cost approximately £3000/house.

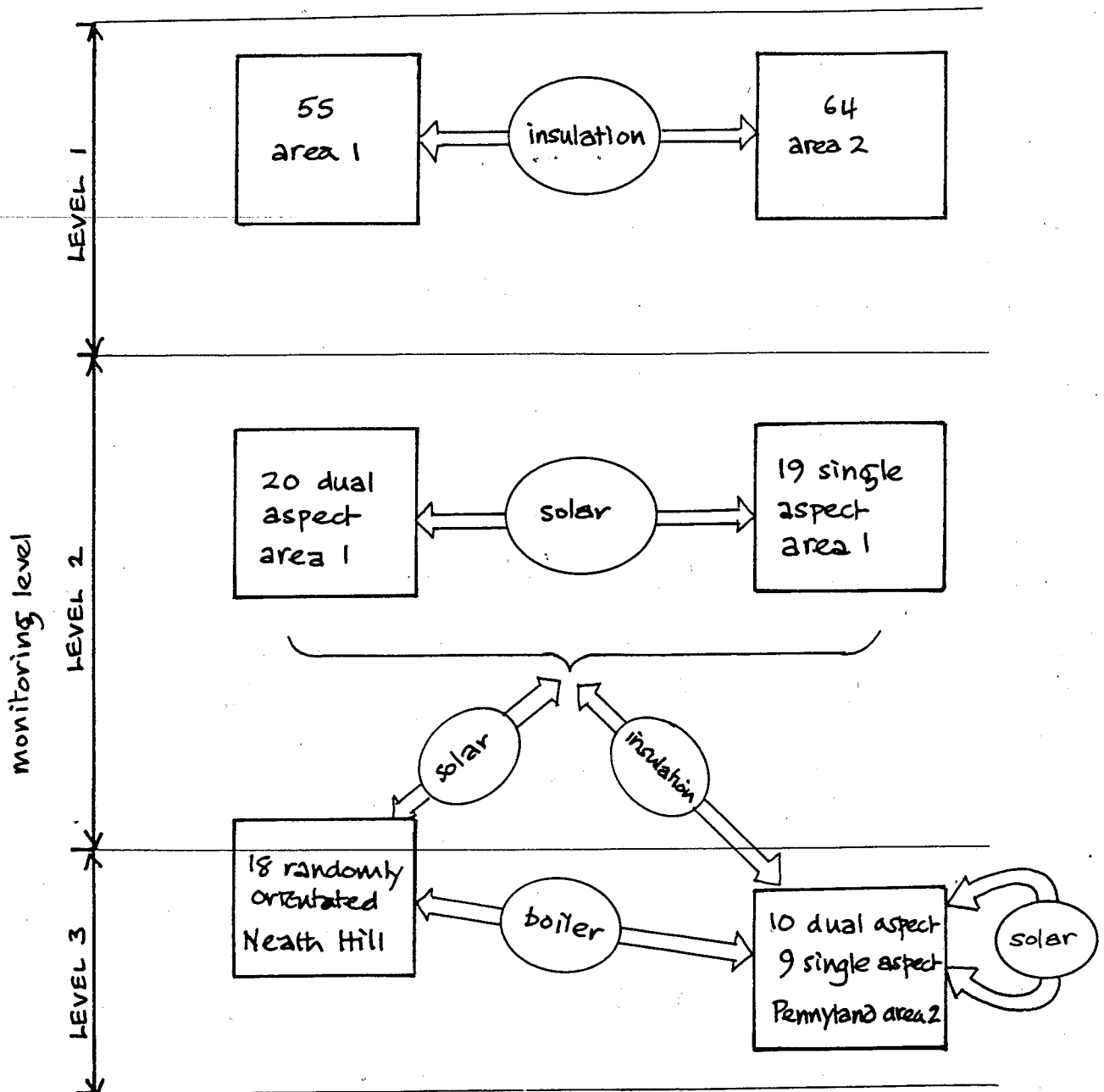
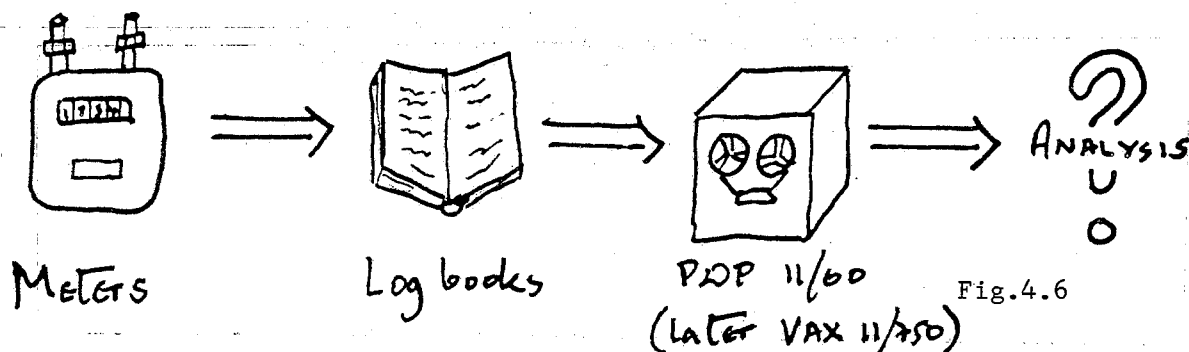


Figure 4.5 The levels of monitoring and comparative groups of houses at Pennyland

4.4. Data collection, cleaning and quality

When the Pennyland project was being planned, techniques of remote data collection in housing field trials were in their infancy. Since it was planned to log data from the Pennyland and Neath Hill houses at weekly or monthly intervals, it was decided to record the data in the field manually in log books, and to transfer the data manually from these to a computer on campus. This system is summarised below:



This method of data collection and storage has a number of advantages:

- a) low capital costs. The cost of wiring the whole estate would have been astronomical.
- b) no modification of gas and electricity meters required.
- c) no possibility of physical disruption of cabling to houses by water, gas or electricity boards.
- d) primary database not liable to loss through computer failures.
- e) a meter reader is a human being and gathers much more than just numbers.

The data were recorded and transferred to the computer by a technician. The method used for entering the data went through two main stages. Initially the whole task was carried out using programs written for the purpose. The aim of this was to cut down the amount the technician needed to know about the computer in order to do the job. The final version makes use of the system editor to preformat the data, and then uses a program called "kool" to add the data to the database. The database is kept in a compact (and unreadable) form to save space. The data is converted back to a readable form by a program called "look" for inspection or passing on to further analysis programs. See Appendix 6 for further details of these programs.

The computer chosen for the project was the Open University Technology Faculty's PDP 11/60 running under the Unix operating system. This was replaced in early 1983 by a VAX 11/750 running an improved version of Unix. It was decided to keep the database permanently on disc, for speed of analysis. This posed no great problem as the final database occupied under one Megabyte. The database was written to tape at daily, weekly, monthly and 3 monthly intervals. The choice of computer and the design and implementation of the database were undertaken by Jeremy Chatfield, and indeed until his arrival no serious thought had been given to these aspects of the project.

It is important that in future projects researchers do not underestimate the computing problems involved in recording large amounts of data. This project and the Linford project have shown that essentially every data record will have to be checked to see whether it is valid. This can be automated to a certain extent but basically it requires visually inspecting all the data and having computer programs available to change any detected errors. This is known as 'data cleaning'.

4.4.1 Problems, reliability and maintenance

All projects have their monitoring problems and this one is no exception. The problems have been fairly mundane, though, and not quite up to the standard of disasters that have befallen other projects (such as having lightning strike the datalogger!).

In order to keep the catalogue of problems to a minimum only those that seriously affect the analysis of the data will be described. They are:-

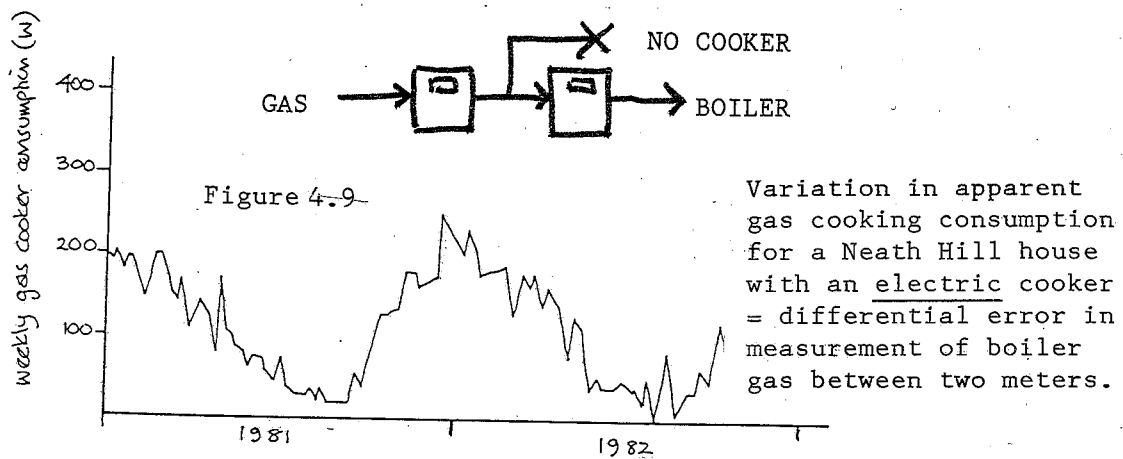
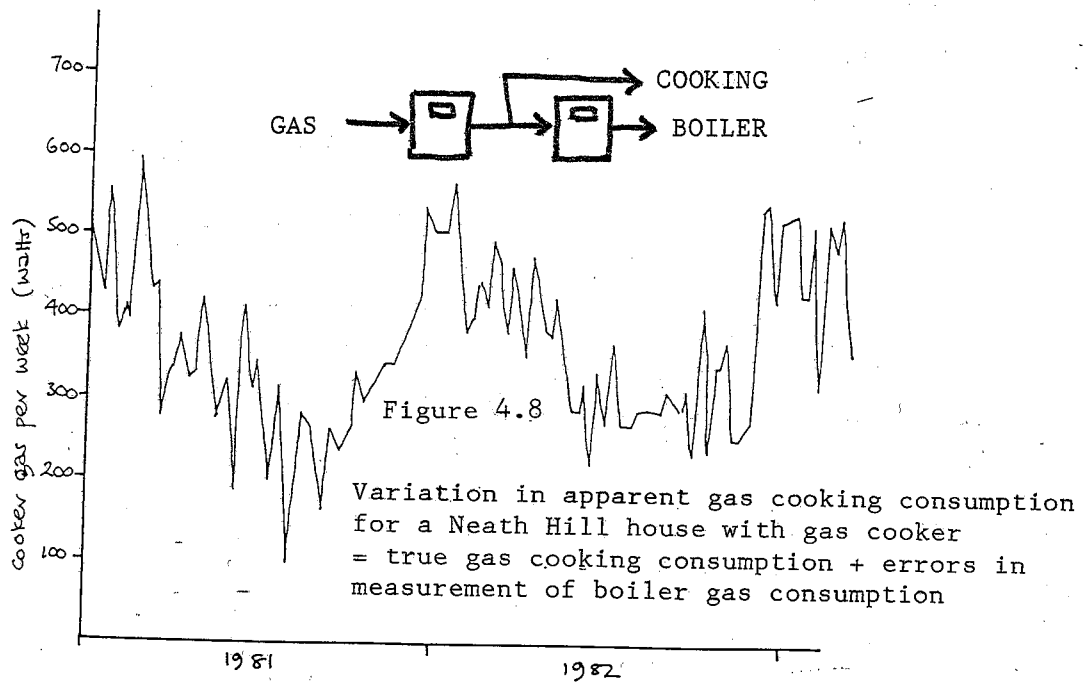
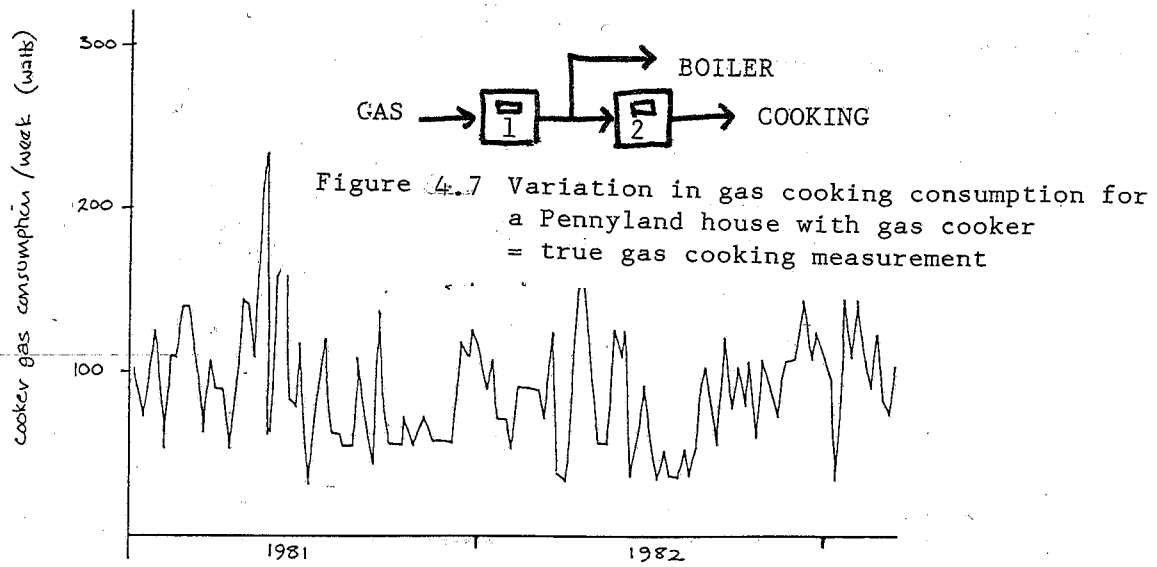
- a) Different connections of the cooking gas meter at Neath Hill and Pennyland.
- b) The gross unreliability of the heat meters and their remote readouts.
- c) The precise siting of the external temperature sensors.

With these exceptions, the gas meters, electricity meters and D.T.I.'s have been very reliable. The D.T.I.'s were all tested for two weeks before installation and this is to be recommended for all equipment.

Cooking Gas Meters

A major problem was discovered when the gas cooking consumptions were compared between Neath Hill and Pennyland and found to be substantially different. The difference appears to be due to the fact that the two gas meters installed had been connected in different ways.

PROBLEMS OF COOKING GAS MEASUREMENT



In the Pennyland estate, the extra gas meter had been connected to record gas cooking consumption, as intended. At Neath Hill, the extra meter recorded gas boiler consumption and the cooking had to be worked out by difference. Since the cooking consumption only amounts to 5-10% of the total gas use, errors in measurement of about 2% in each of the gas meters could have rather drastic effects.

The resulting confusion is illustrated in figures 4.7-4.9, the Neath Hill cooking gas consumption effectively being the real consumption plus the errors of both meters in registering the boiler consumption. In the limit, in figure 4.9, we have a large calculated gas cooking use for a house equipped with an electric cooker!

The result of this confusion is that we are not sure what the real cooking gas consumption of the Neath Hill houses is. This injects a large amount of uncertainty into what was supposed to be a simple comparison between two groups of houses. This will be discussed more in section 5.4.

The moral is to measure what you want to know directly and not try to work it out from something else. It is also essential to measure everything in the same way in all groups - it is the houses that are under test, not the monitoring equipment!

Heat Meters

At the outset of the project heat meters did not have a very good name for reliability or accuracy. It was hoped that the type used in this project would have improved the image. In practice they have been rather unreliable, mainly due to jamming of the flow meters.

The turbines of the flow meters were protected by a fairly coarse sieve with an embedded magnet. It was not appreciated at the outset of the project that this type of flow meter is normally used in properly filtered water (this wasn't discovered until well after they had been installed). The normal murky contents of a central heating system caused the filters to block repeatedly, preventing water flow. This occasioned many callouts from the occupants of the houses to unblock the filters and get the heating systems working.

The heat meters also were provided with a remote readout made at the university. These readouts were not tested before they were installed, with a consequent high failure rate.

Here it would have been highly desirable to test out a couple of meters in sample central heating systems before starting the experiment. It would have required having sample meters about six months before installing the rest. As it was heat meters were being installed at Neath Hill before the official contract for monitoring with the University had actually been signed!

The effect of the general unreliability has been that although there are enough readings to work out the boiler efficiencies and some space and water heating consumptions, most analysis has had to proceed from weekly gas consumption data. Space and water heating consumptions for the majority of houses have had to be calculated by the rather complicated process described in section 5.6.

External Temperature Sensors

As will be explained in the next chapter, quite small differences in average temperature difference can be important when making energy comparisons. It is thus vital to be sure that these are not due to systematic differences in the siting of the monitoring equipment.

The external temperature sensors for the D.T.I.'s were generally mounted over the house meter cupboard. In 15 of the 20 dual aspect houses in Pennyland Area 1, this meant that they were on the south, and hence warmer, side of the house. Nor were they particularly well shielded from direct sunshine. All of the other Pennyland houses have the meter cupboards on the north side and are reasonably well shielded.

Some of the Neath Hill houses had the same problem, with external temperature probes on the unshaded east or south walls. Sun shields were fitted to some houses in the summer of 1982 (i.e. after the main period of monitoring analysed in this report). These shields were probably rather ineffective, since on still-air days, the probe would still be within the boundary layer of warm air rising up the wall of the house. The importance of the error is not known, but it could easily make a difference of 0.5°C to the average heating season ΔT .

The problem is also present to a certain extent in the siting of the internal temperature probes, particularly in how many of the three sensors are on the south, and warmer, side of the house.

The effects on analysis are twofold. It creates an uncertainty over the energy consumption differences between single and dual aspect houses, and, since the effect is bigger on sunny days than on dull ones, upsets the determination of solar apertures by regression. This latter topic is discussed further in the Linford report.

There is no doubt that these problems could have been avoided with more thought and perhaps the provision of a slightly more complex external temperature sensor mounted well away from the house walls.

More general advice on monitoring methods will be found in Chapter 8.

4.4.2 Data Cleaning

One of the most tedious tasks that had to be completed before the data could be analysed in earnest was data cleaning. It cannot be stressed how important this is. Every data record has to be checked for validity and freedom from equipment errors, recording errors and 'occupant errors' (it is no use monitoring an empty house!). The process is essential before any statistical analysis is undertaken, since regression procedures are very sensitive to any 'outliers' or spurious data points - it is the houses that are under test, not the researchers' mistakes.

Appendix 9 describes in detail the cleaning process and figure 4.10 shows examples of error correction.

4.4.3. Data quality and availability

Appendix 9 also summarises information on when data was recorded, for which variables, in which houses. It also summarises the quality of the data for the main groups of houses, for each variable.

An example, of the availability of monitoring equipment in Pennyland area 2, is shown in Figure 4.11. As students of boiler efficiency require both heat meters to be working, it is useful to know when this is the case: Figure 4.12 shows this for Pennyland area 2.

The recording of data availability is important since the project data has been archived in the Better Insulated House database and it is to be hoped that further analysis will be undertaken in the future. Subjects such as the cross-correlation of fuel consumptions for individual houses and the social survey interviews would be highly fruitful.

The monitoring technique used at Pennyland and Neath Hill is potentially susceptible to a missing data rate of about 1% after data cleaning. This can be seen from the performance of the gas and electricity meters. This is more than adequate for most purposes. However to realise this rate for the less reliable and more sophisticated equipment, the DTI's and the heat meters, clearly requires more attention to maintenance and feedback between technicians and researchers than was achieved on this project.

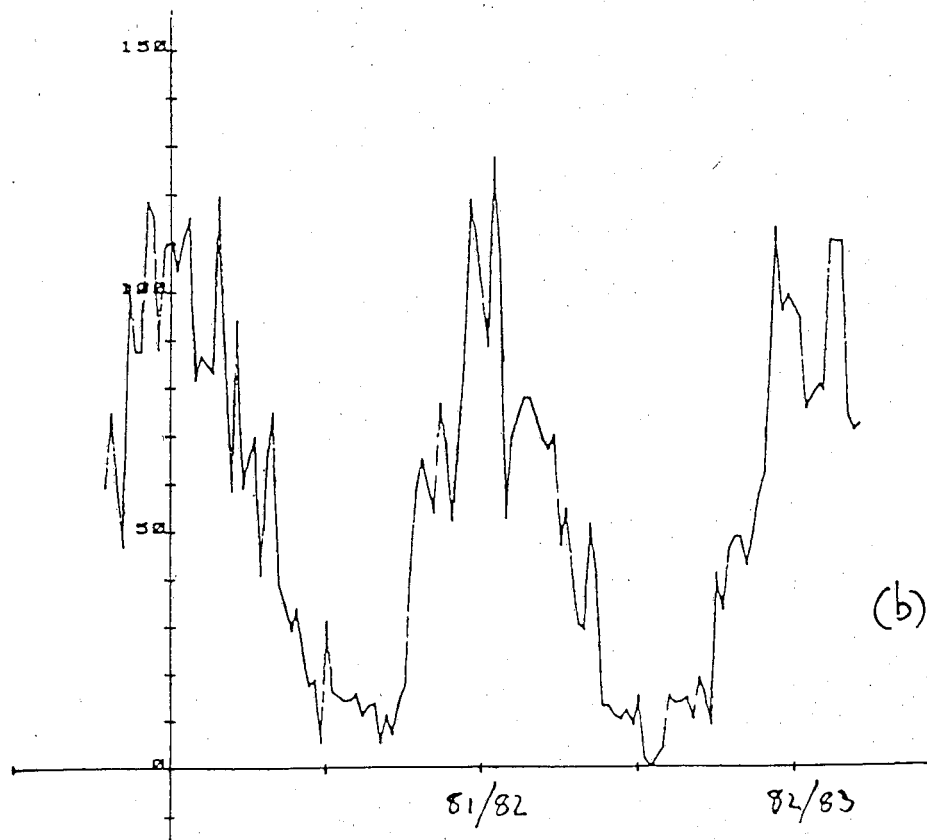
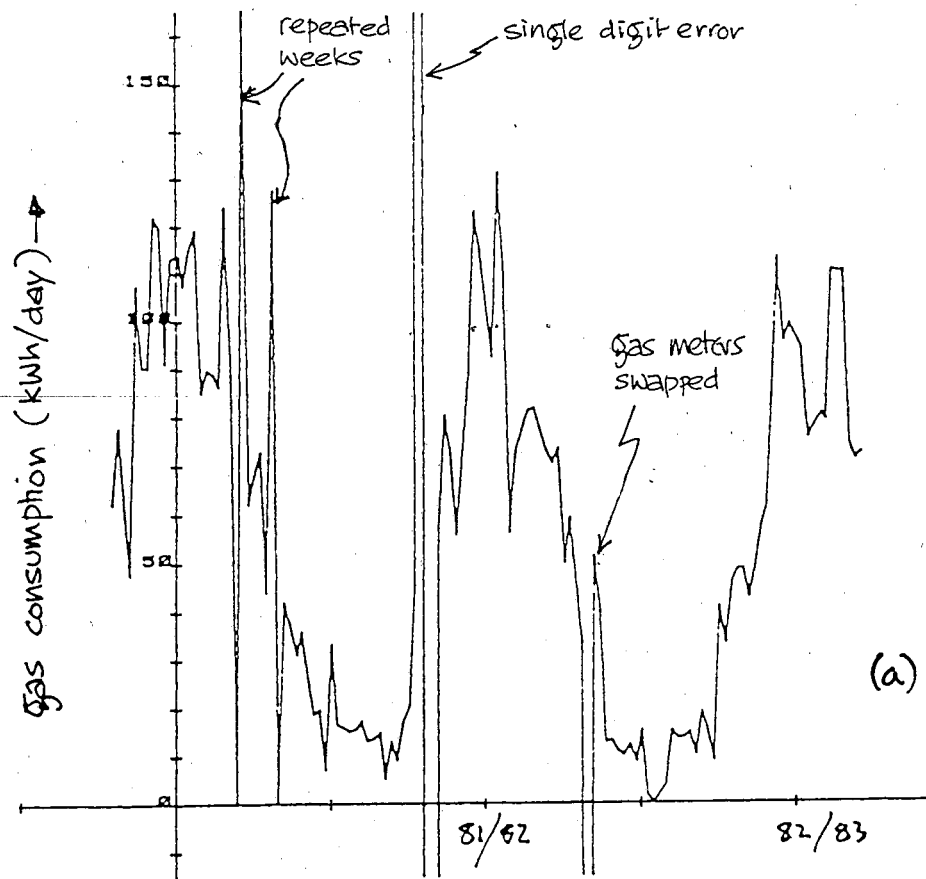


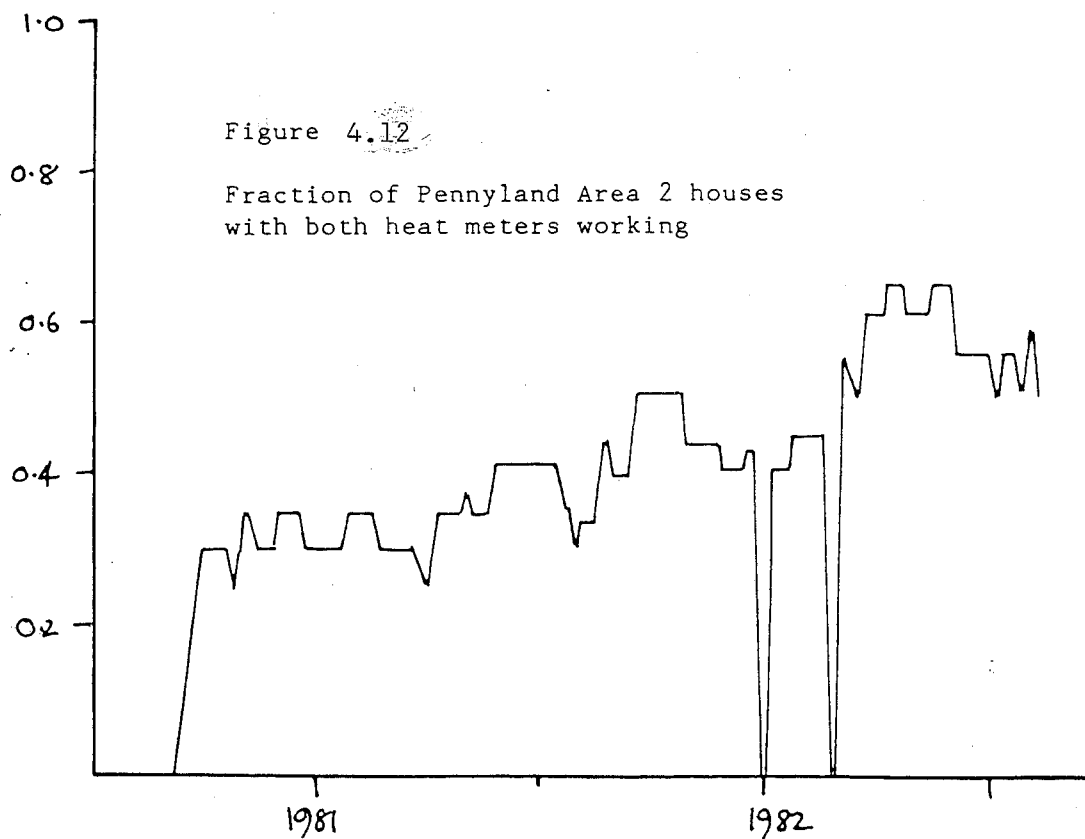
Figure 4.10 Gas meter data (a) in raw form
(b) after cleaning

Availability of monitored data

Figure 4.11

Pennyland area 2, intensively monitored.

	81												82																	
	o	n	d	j	f	m	a	m	j	j	a	s	o	n	d	j	f	m	a	m	j	j	a	s	o	n	d	j	f	m
g1																														
e1																														
g2																														
dti																														
h1																														
h2																														



4.5. Social Survey

4.5.1. Introduction

The survey broadly aimed to discover whether Pennyland residents liked their homes, whether energy issues were an important element of their satisfaction and specifically whether they perceived benefits or disbenefits associated with the Pennyland heating systems.

The social survey was carried out in May, June and July 1982 using personal interviews. 123 Pennyland households out of a total of 177 and 15 out of 20 in a control group on the Neath Hill Estate were interviewed. The control group were those houses which had been chosen for physical monitoring of fuel consumption. This group of houses had been selected for its physical attributes which differed from the Pennyland scheme as they met the 1976 Building Regulations standards of insulation and were randomly orientated and were overshadowed. In general, the Neath Hill sample is too small for statistical comparison.

4.5.2. Characteristics of the Pennyland and Neath Hill Sample

The survey found that the Pennyland population was younger than that of England and Wales, comprising mainly young couples or young families in two or three person households. Pennyland households were better off than is usual for local authority housing, but earn less than the population in general. The car ownership rate in Pennyland was higher than in England and Wales. The Neath Hill sample was slightly older with larger families and earned a little less than their Pennyland counterparts.

4.5.3. Residents' attitudes towards the house and estate design

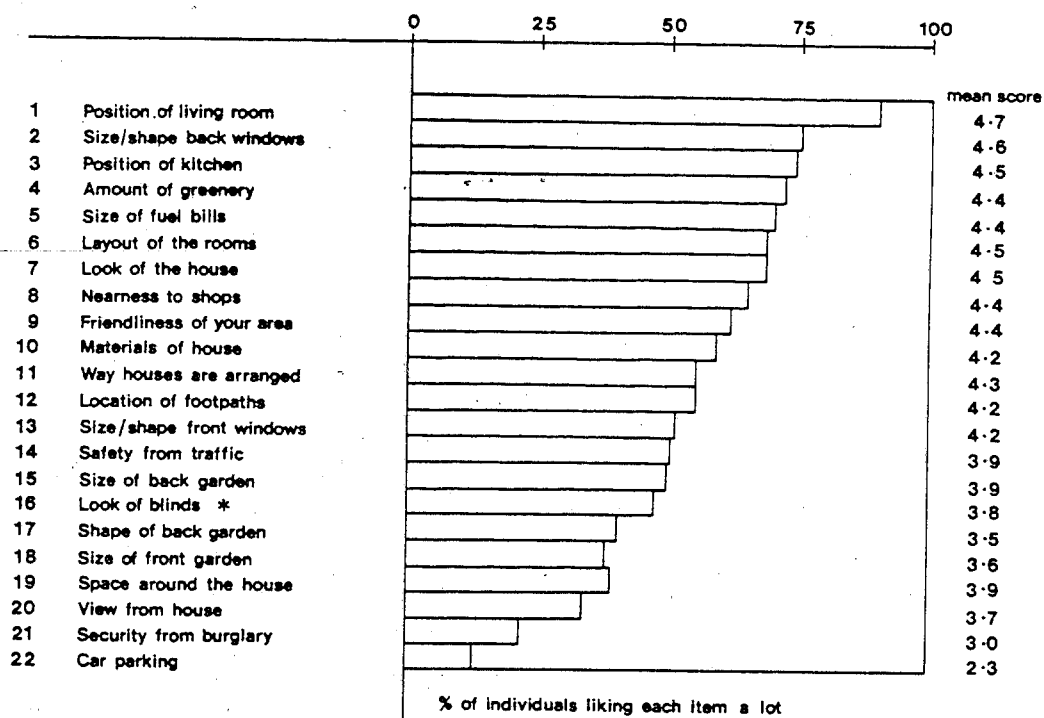
Pennyland was a popular estate, over half of the residents had selected it as their first choice. In choosing their house the special energy saving features had not rated highly as a reason for choosing the house. People looked for a well designed estate, and a good neighbourhood where the houses are of 'traditional' appearance and construction.

Once living in the house, low energy costs were seen as a main advantage and good insulation as a reason for considering the house as good to buy and easy to resell.

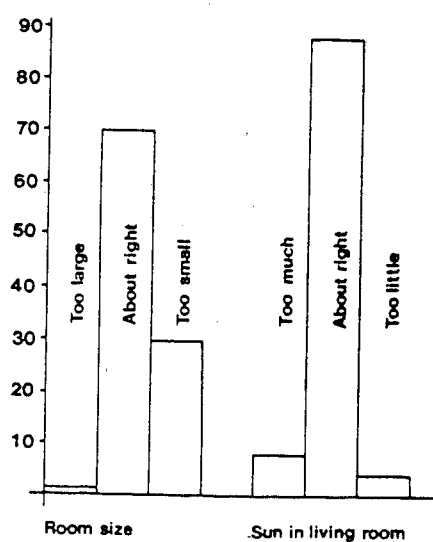
Some of the features of Pennyland most liked by residents relate to the passive/low energy designs of the houses: their internal layout, their large sunny back windows and the size of their fuel bills. The appearance of the house, the general layout of the estate and landscaping were also very satisfactory. The main problems related to the lack of adequate car parking, the privacy problems created by the back-to-front houses and the garden mounding which was intended to act as a privacy barrier. Residents were also concerned about security from burglary and complained about the inadequacy of door and window locks.

Figure 4.13

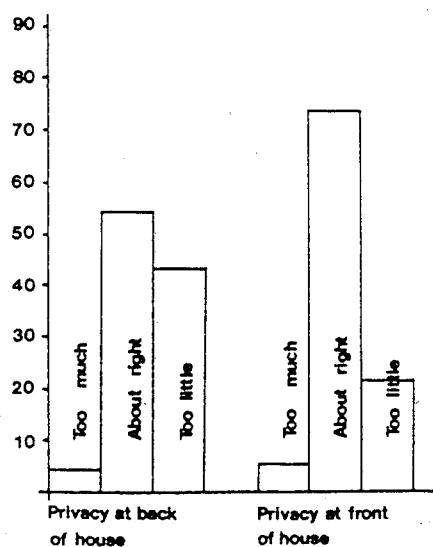
DIGEST OF SOCIAL SURVEY RESULTS



Popularity of 22 characteristics of Pennyland houses



Room Size and Sunshine



(South)

(North)

Privacy

When asked to choose between the Pennyland layout and a more detached housing layout, half the residents were prepared to spend an extra £15 on fuel bills to gain advantages of more privacy and space. Few were prepared to pay an extra £30 in bills for a less attractive, Neath Hill type, layout which did not offer any extra advantages of space and detached houses. A straight terrace layout that would have been cheaper to heat was also not so popular.

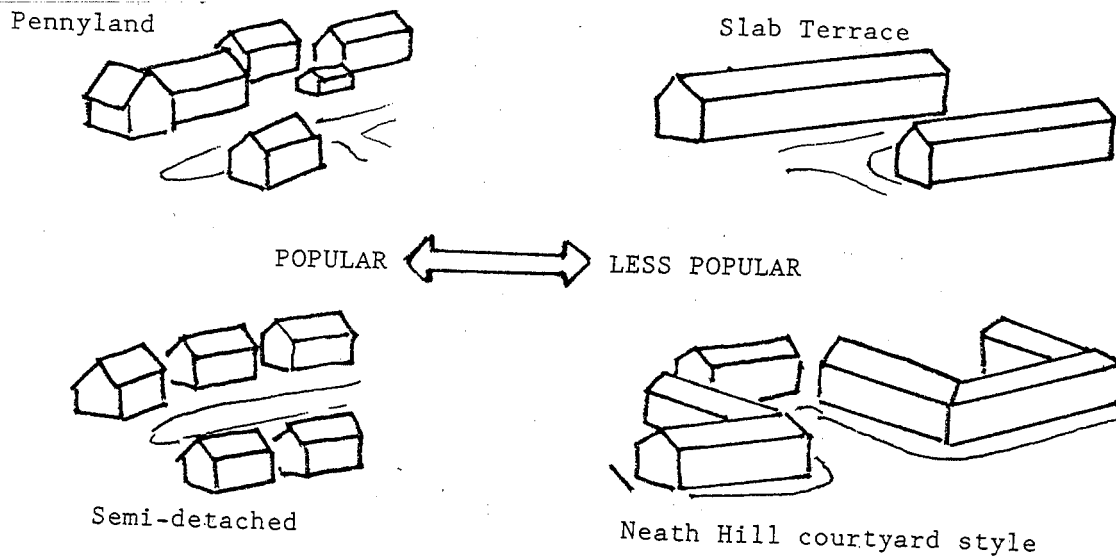


Figure 4.14 Social Survey popularity of estate layouts

4.5.4. Residents perceptions and attitudes towards their heating system

Pennyland residents were generally happy with their heating systems, 87 per cent were more satisfied with their present system than with the system in their last home.

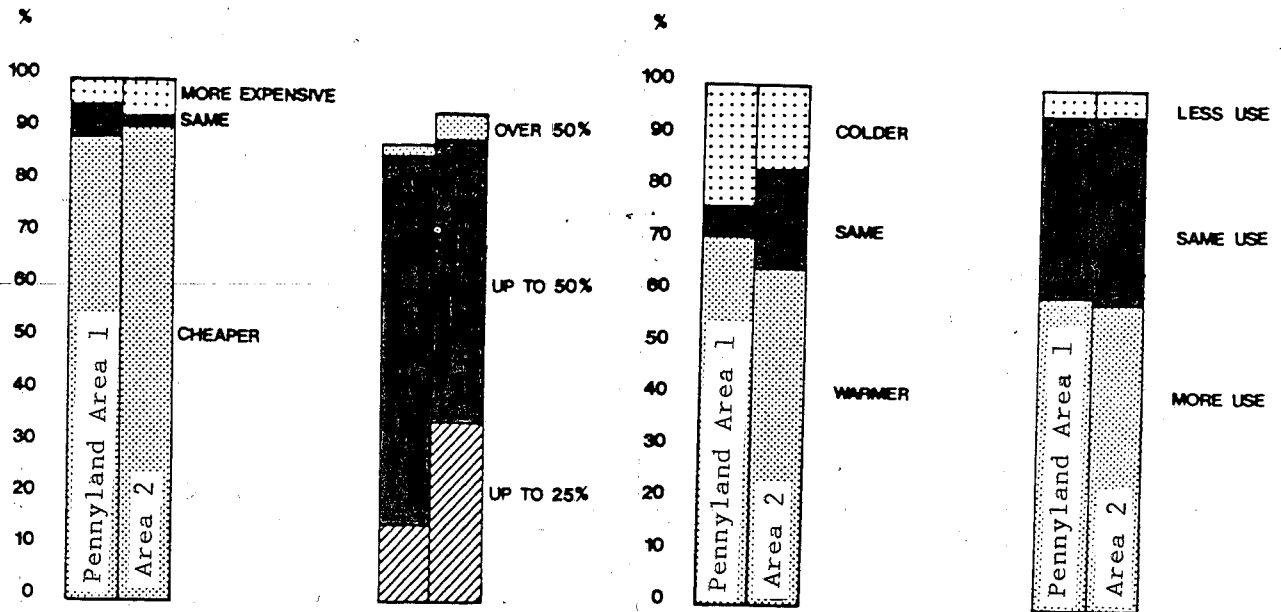
Eighty one per cent of the households in Pennyland were able to keep their house as warm as they would like. This proportion is well above the average for households living in Milton Keynes new town rental property. The warmer temperatures enabled 60 per cent of families to make more use of their rooms than in their previous house.

Curiously, despite similar measured internal temperatures at Neath Hill, only 40% felt that they could keep their house warm enough. This may be due to the higher air infiltration rates there.

Most important, only 3% of Pennyland residents said that they could not afford to keep their house warm enough, compared to 28% in a wider Milton Keynes survey.

Figure 4.15

DIGEST OF SOCIAL SURVEY RESULTS



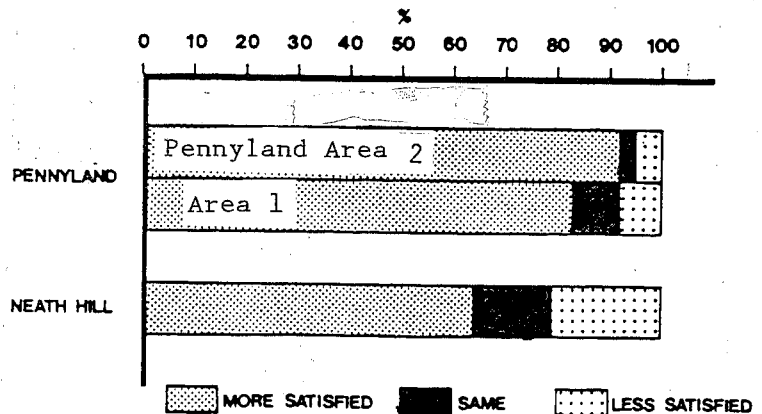
Comparison of
fuel bills with
previous home

Estimates of
amount saved
on fuel bill

Is your house
colder or warmer
than the previous
home?

Do you make more
or less use of the
rooms?

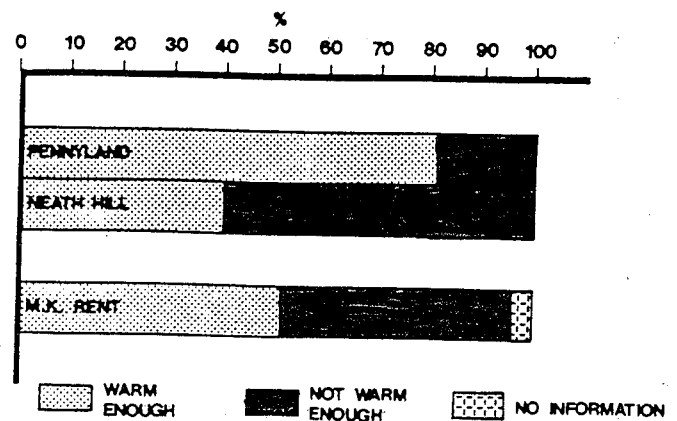
Comparison with heating
system in previous home



Are you able to keep
your house warm enough?

Survey Date

AUTUMN '83



Ninety one per cent of Pennyland households felt they were making savings on their fuel bills, and sixty seven per cent claimed to be making savings of over a quarter. Generally the Pennyland Area 2 houses scored higher in terms of comfort and estimated savings on fuel costs. They were also less prone to condensation and mould growth but there was a tendency for them to overheat in summer slightly more often than the Area 1 houses particularly when the high insulation was combined with orientation to the south.

4.5.5. The residents energy management behaviour

A majority of people had taken some action to improve the thermal performance of their houses, most commonly draught proofing or heavy curtains. Most people were using their heating controls effectively but most did not remember being instructed by anybody on how to do so. The main problems seemed to be heating unoccupied bedrooms and leaving hot water switched on constantly. The windows and shutters were not always used most efficiently but this was generally for good reasons such as problems with condensation or a need to clear normal household smells.

It can be concluded that whilst energy issues are not a major reason for choosing a particular house they are an added bonus and are very important in establishing favourable attitudes towards the home.

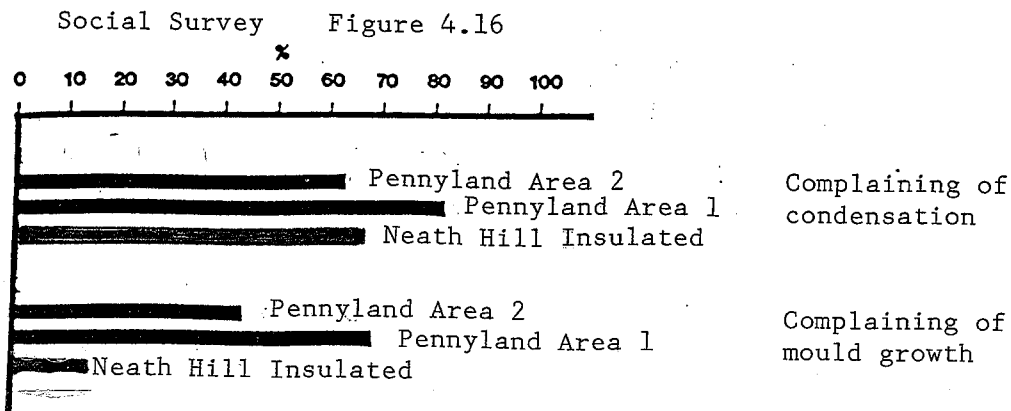
4.5.6. Condensation

In addition to the measurements of moisture content in the roof timbers the residents of Pennyland were asked about condensation in the houses.

This is especially important since the estimated air change rates in these houses is likely to be very low, of the order of 0.2-0.3 ac/h.

73% of Pennyland residents said that their houses suffered from condensation. It was more prevalent in the less well insulated Pennyland 1 houses (see figure 4.16 below). The condensation appeared mainly between the panes of the double glazing and on external doors. It is likely that slight modifications to the design of the double glazing could alleviate some of these problems.

Condensation complaints were not significantly different at Neath Hill. 66% of the residents interviewed there said they had condensation.



56% of Pennyland residents said that their houses suffered from mould. None of the residents considered it a serious problem, though. Usually it appeared on upstairs window frames, the downstairs W.C., the bathroom or under the kitchen sink, for a relatively short time in winter.

Complaints of mould growth at Neath Hill were much lower. Only two households out of the sample of 15 (i.e. 13%) said that they had any mould growth.

Despite the low estimated air infiltration rates at Pennyland, it is likely that a moderate amount of window opening takes place. 52% of the residents said that they were in the habit of opening the windows on cold sunny days with the heating on, and 95% said that they aired the bedrooms by opening windows in winter.

Measured window openings on the companion Linford project showed wide variations from house to house, with most window opening concentrated towards the end of the heating season and very little opening of kitchen, W.C. and bathroom windows.

Generally it seems that condensation has not been a serious problem in the Pennyland houses. However, the higher incidence of mould growth suggests that it would be unwise to make any future house designs more airtight than these without some provision for forced mechanical ventilation. This should be directed to critical areas such as the kitchen, bathroom, and W.C.'s.

4.6 Pressure Tests

Pressure leakage tests were carried out on four houses at Pennyland (three in Area 1 and one in Area 2) and on three houses at Neath Hill. They were carried out by British Gas in conjunction with the research team. The test involved mounting a panel over a window opening and using large fans to pressurise the house (see figure 4.17). By measuring air flow rates at various pressure differences, it is possible to calculate the air flow at a standard pressure difference of 50 pascals between the inside of the house and the outside.

The results can be used to compare the relative leakiness of different house designs. It is possible to relate the pressure test results to expected air infiltration rates due to wind effects and stack effects (i.e. the fact that the warm air inside a house tends to rise and creates air movement), by using a crude model. This model, created by P.Warren of the B.R.E., is described in Appendix 7. Other ideas, due to D.Etheridge of British Gas, will be found in the Linford Project Final Report.

The pressure test results show that whilst the houses at Neath Hill are similar to other 'normal' U.K. houses tested elsewhere, the Pennyland houses are significantly less leaky (see figure 4.18). The houses at Linford were also pressure tested and the test house had the air infiltration rate measured directly using the decay of an injected tracer gas. These measurements tended to confirm the basic theory relating air infiltration to wind speed and stack effects.

The Linford measurements showed that those houses were, like the Pennyland ones, significantly more airtight than normal U.K. houses. The test house measurements also allowed the estimation of a seasonal average air infiltration rate.

The Pennyland pressure test results, although very good, are still higher than those now permitted by the Swedish building regulations.

Based on the pressure test results, the average air infiltration rates at Neath Hill over the heating season would be 0.3-0.8 ac/h. For Pennyland Area 1 it would be 0.15-0.35 ac/h and for the Area 2 house tested, 0.1-0.25 ac/h.

To each of these air infiltration rates must be added an extra component due to window opening. Window opening was actually measured in the Linford houses, allowing some estimate of the ventilation rate (i.e. including the effects of the occupants) rather than just the air infiltration rate (i.e. with all the windows shut).

Figs. 4.19 and 4.20 show two extreme estimates of ventilation rate over the heating season, one from a house where the windows were normally kept shut, the other from one where they were opened extensively at the ends of the heating season. They do, perhaps, illustrate the folly of assuming a constant ventilation rate over the heating season.

Based on the Linford measurements, it would appear that on average window opening adds about 0.1 ac/h to the seasonal average air infiltration rate. This implies average ventilation rates at Neath Hill of 0.4-0.9 ac/h and 0.2-0.45 at Pennyland.

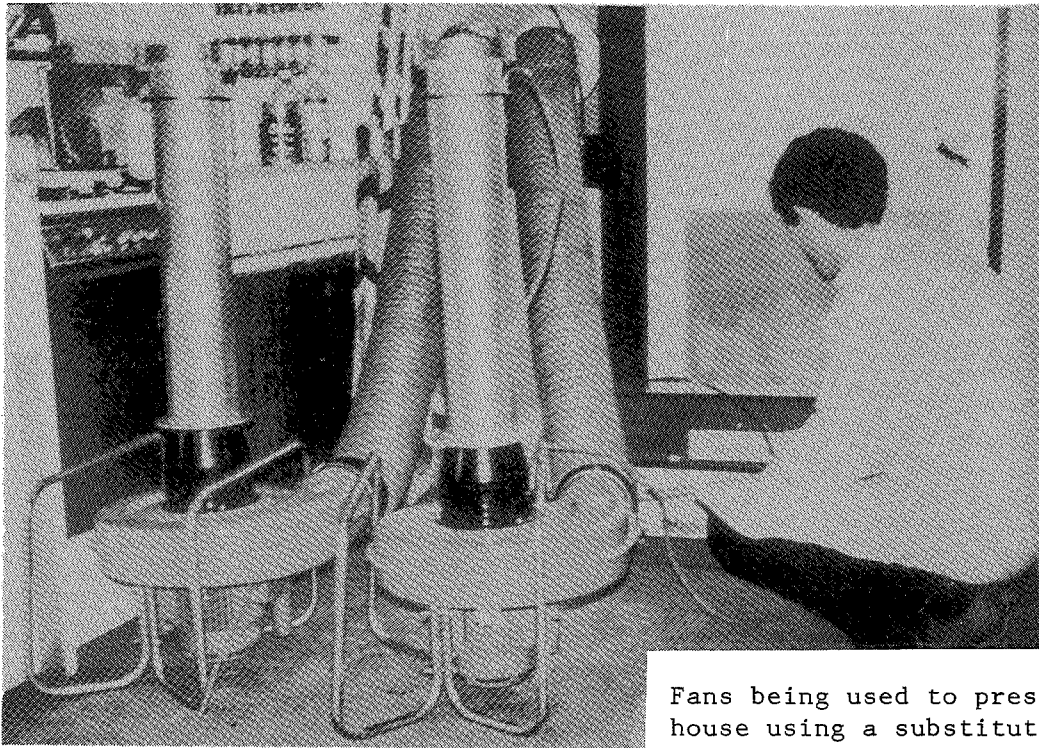


Fig.4.17

Fans being used to pressurise a house using a substitute window.

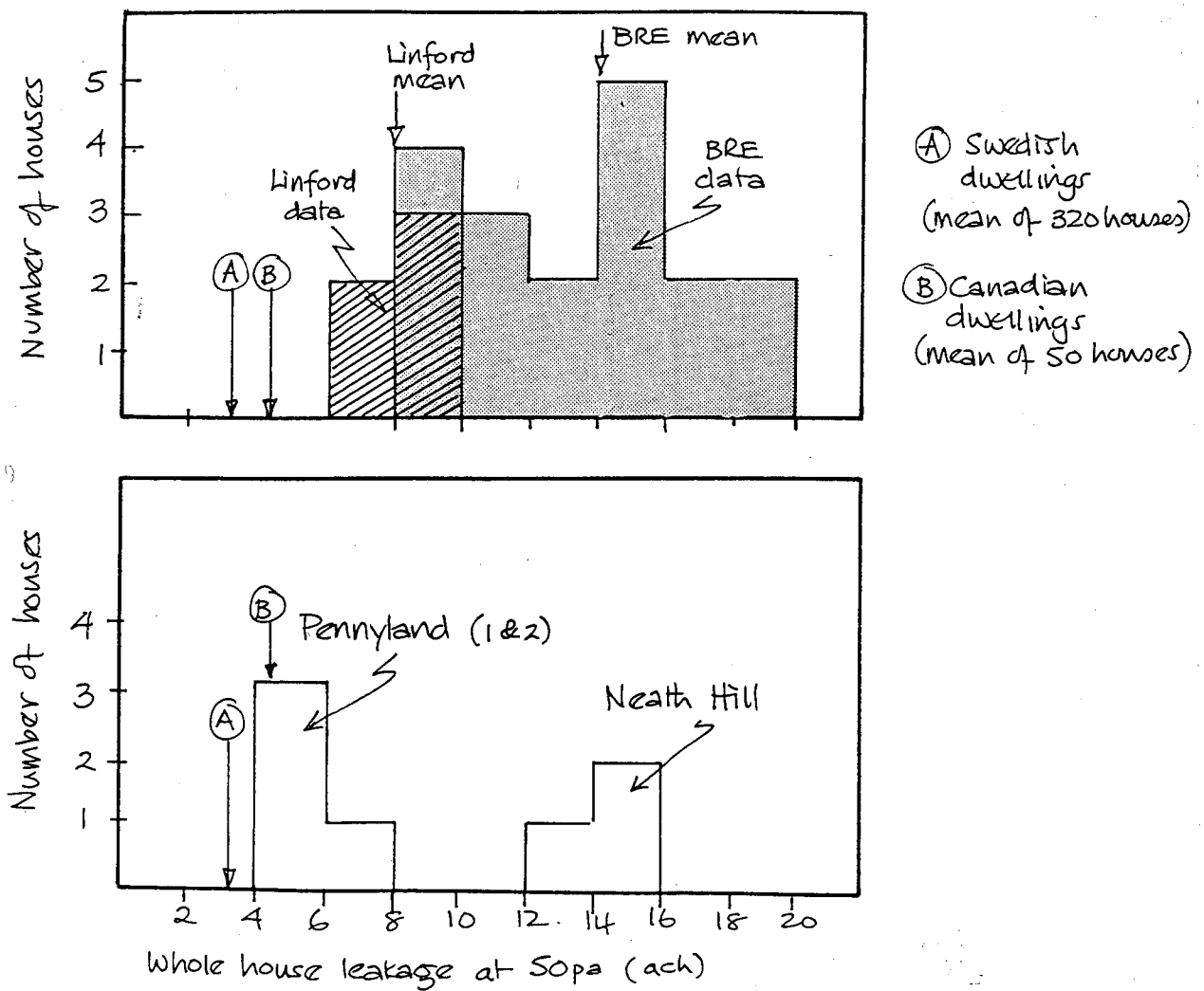
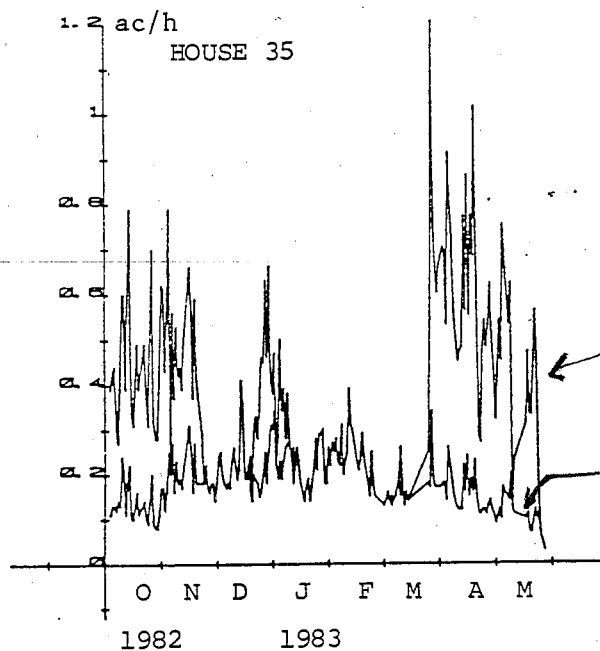


Figure 4.18 Results of pressure tests at Neath Hill and Pennyland compared to the Linford results, a BRE sample of 'normal' modern U.K. houses and some Swedish and Canadian houses.



LINFORD OCCUPIED HOUSE MEASUREMENTS

Figure 4.19

House showing considerable window opening at the ends of the heating season.

Ventilation rate estimated from test house measurements and measured window openings

Infiltration rate assuming windows shut

The air infiltration rate estimates have been made using a model fitted to Linford test house measurements relating infiltration rate to wind speed, direction and ΔT . The model has been extrapolated over the year using measured weather data.

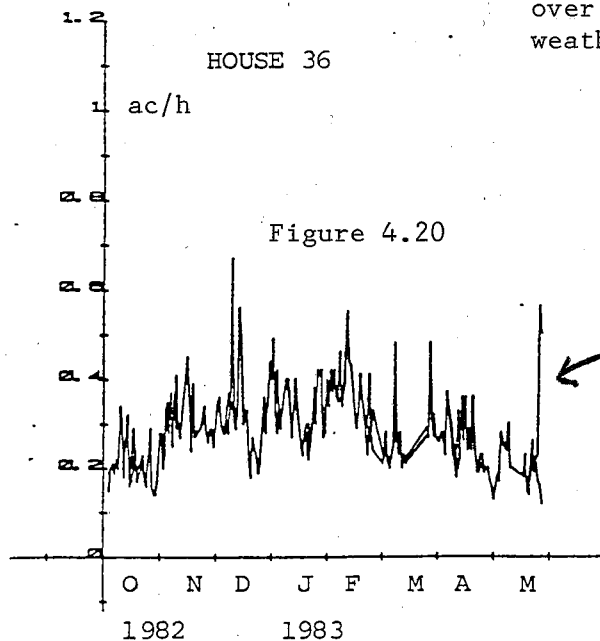


Figure 4.20

House with almost no window openings shows little difference between air infiltration rate and ventilation rate.

Given the measured average winter temperatures in the different groups these ventilation rates imply different heat losses over the heating season:-

Table 4. 2 Ventilation heat losses at Neath Hill and Pennyland

Site	Assumed infiltration rate (ac/h)	Total ac/h	Average temp. diff.	Ventilation heat loss (kWh/yr)
Neath Hill Ins.	0.5	0.6	13.1	3070
Pennyland 1	0.25	0.35	11.8	1610
Pennyland 2	0.18	0.28	12.4	1350

Although there are considerable uncertainties in deducing ventilation rates from pressure test results, there does seem to be a considerable difference between Neath Hill and Pennyland Area 1, amounting to about 0.3 ac/h or 1500 kWh/yr in energy terms. This energy saving accounts for about a third of the space heating saving between the Neath Hill insulated houses and Pennyland Area 1.

The low air change rate at Pennyland is likely to be due to the method of construction, the poured concrete inner leaf being likely to be a major feature. The leakier Linford houses differ only from Pennyland Area 2 houses in using dense concrete blockwork for the inner leaf instead of a poured concrete construction.

The Pennyland Area 2 houses are possibly more airtight than the Area 1 houses, though only one Area 2 house was tested. If this is true then it is most likely to be due to the good performance of the Sashless double glazing.

In practice the low air change rates at both Linford and Pennyland have been produced by attention to detail:-

Inclusion of draught lobbies (see figure 4.21)

Filling of cavity

Use of balanced flue boiler

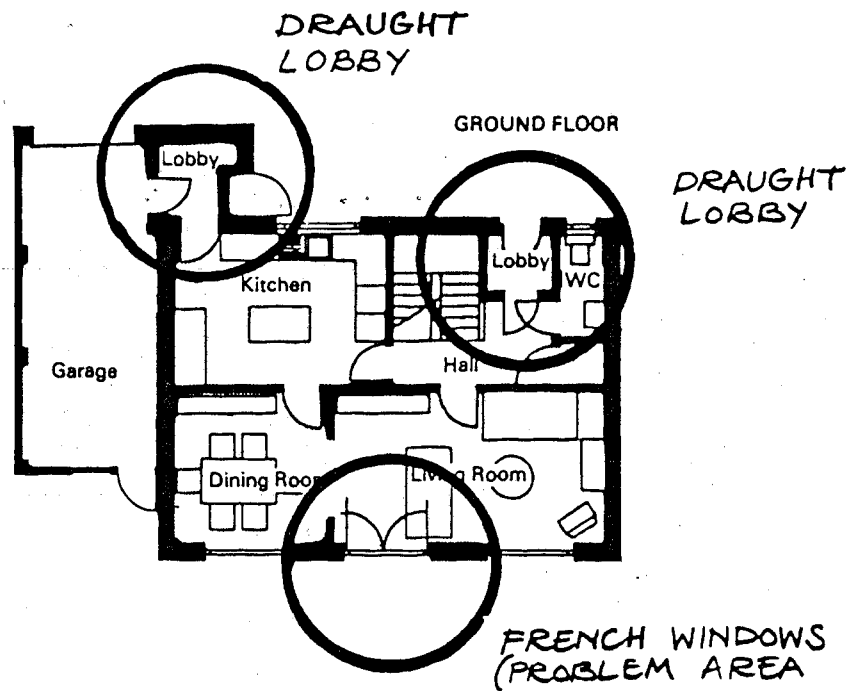
Use of well sealed glazing

The ventilation energy savings are a useful bonus in a better insulated house, since the ventilation losses were expected to dominate the energy balance as they became proportionately larger. In practice they have reduced in proportion with the insulation heat loss reductions.

The low air change rates do bring with them concern about condensation and mould growth (dealt with in the previous section), and, on the right ground conditions, radon gas concentration.

Given the comments on mould growth in the previous section, it would perhaps seem wise if U.K. construction practice were to follow the Swedish pattern in attempting to achieve a 'normal' air change rate for a house of 0.5 ac/h. This could be done either by building a very airtight house and installing mechanical ventilation, or by controlling the natural air leakage of the house. A 50 pa pressure leakage of 10 ac/h in a two storey house would give about 0.5 ac/h air change rate throughout the winter. It would help considerably if the 'leaks' were purpose-built to be in the right places (i.e. the kitchen, bathroom and W.C.'s).

LINFORD



PENNYLAND

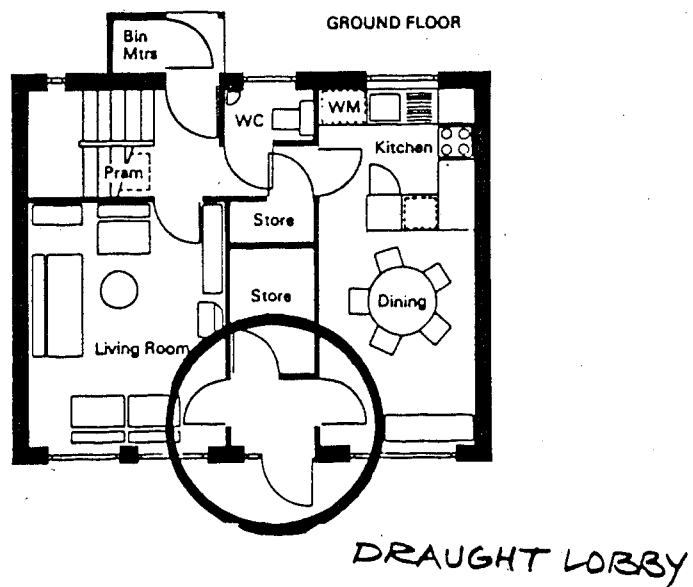


Figure 4.21

Internal planning is important in the reduction of infiltration

4.7 Thermographic Survey

This was a simple survey of both the Pennyland and Linford houses undertaken with an infra red camera. The aim of the survey was to examine the houses for any cold bridging or poorly placed insulation. The surveys were carried out in November 1983 and in March 1984. The November survey was particularly useful as it was carried out in near perfect conditions - very dry with the temperature about -2°C . The March survey was less successful due to rain and a problem with the camera.

Examinations of both the Linford test house and houses at Pennyland showed the heat loss from the ground floor slab. This showed as a hot stripe round the bottom of the houses, and visually at least confirmed the results of the experimental work at Linford which appeared to show that floor heat loss was larger than expected and not much affected by the edge insulation. Figure 4.22 shows infra-red photographs of the lower part of an area 1 house at Pennyland.

Some of the Area 1 walls had a distinct mottled appearance showing the variations in cavity and insulation thickness mentioned in the buildability study (see figure 4.23). This mottling was not visible in the Area 2 houses, though the presence of the wall ties could be seen (see figure 4.24).

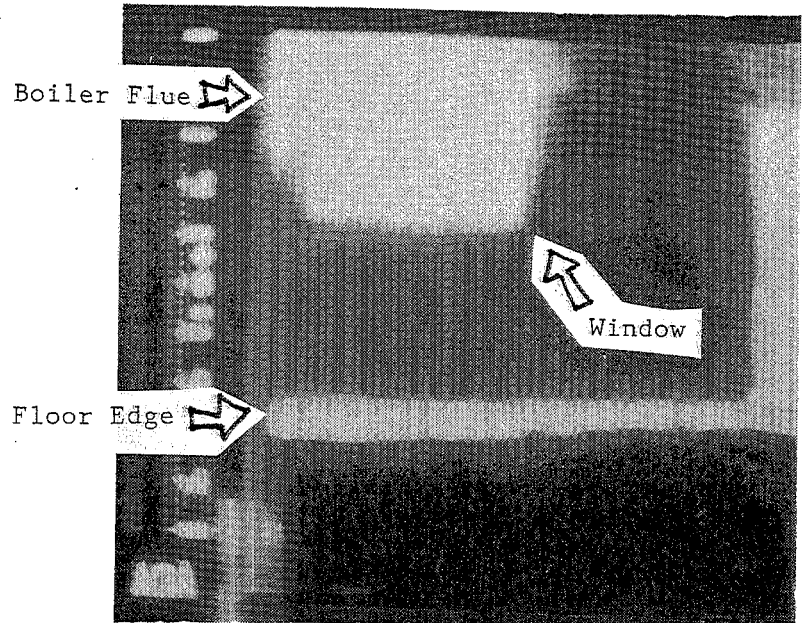
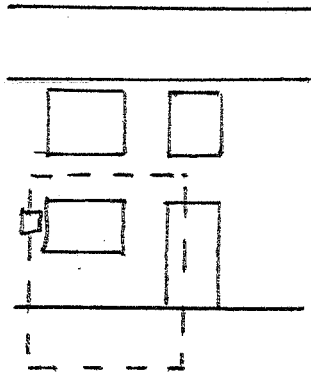
Use of the window shutters was observed in one case at Pennyland, and this appeared to result in reduced heat loss. The window appeared to get hotter towards the top, an effect which may have been due to warm air getting behind the shutters. [See Figure 4.25.]

Observations were made at Neath Hill, but were rather inconclusive. There did not appear to be any evidence of poor wall insulation in these houses, but without knowing what was going on inside the houses that we were looking at, it would be difficult to be sure. One feature that was clearly visible in the Neath Hill houses was the position of the boiler flue, which rises up the inside of an external wall, through the ceiling and out through the ridge of the roof.

Additional observations were made in the Linford test house which were not possible at Pennyland, but which are probably applicable.

The inside of the upstairs ceiling clearly showed the cold bridging of the joists and where some insulation had been omitted under a temporary wooden support used to stabilise the roof trusses during construction. (Examination of a poorly insulated house at Beanhill showed the opposite, the presence of joists was better insulation than the $\frac{1}{2}$ " fibreboard supposedly stopping the heat flow to the outside world!)

The Linford test house showed a significant cold bridge due to the metal lintel over the windows. The Pennyland houses used a split lintel construction which did not produce a cold bridge at this point.

THERMOGRAPHIC SURVEY

WHITE = HOT
BLACK = COLD

Figure 4.22 Heat loss from floor slab edge in Pennyland Area 1 shows as white stripe.

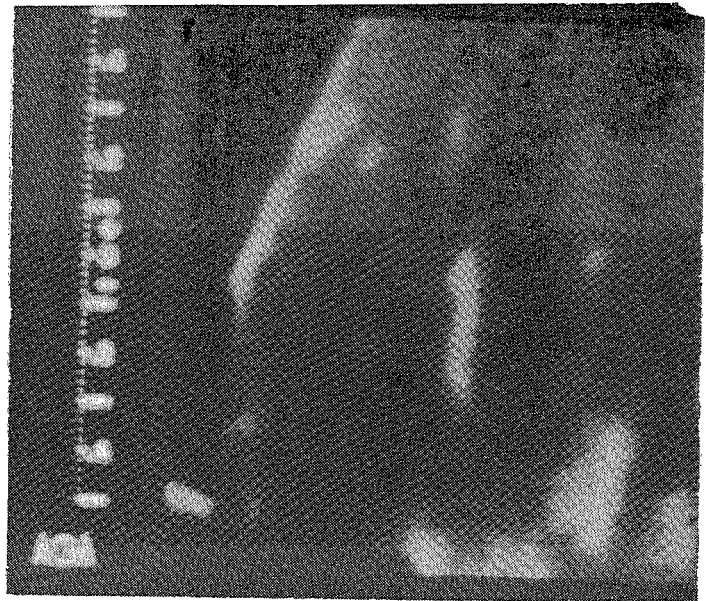
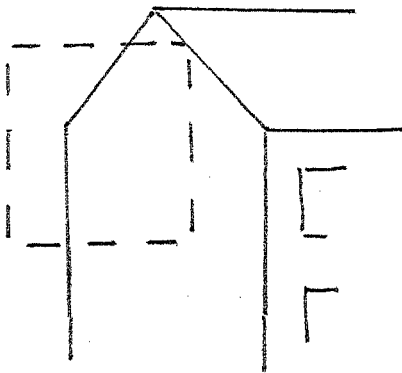


Figure 4.23 Variations in cavity width produce uneven wall heat loss in Area 1.

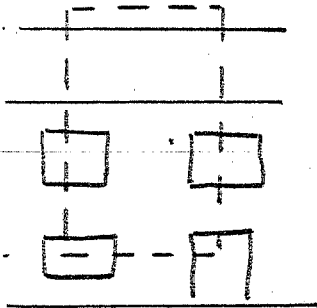
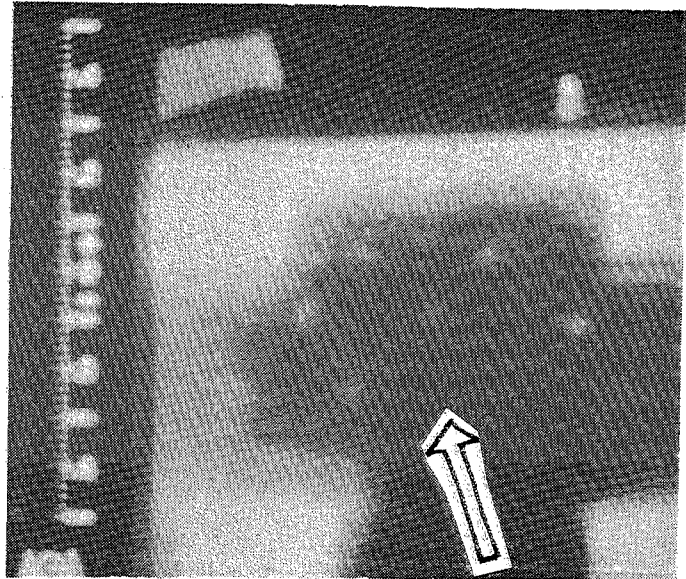
THERMOGRAPHIC SURVEY

Figure 4.24

PENNYLAND AREA 2

WHITE = HOT

BLACK = COLD



White dots show cold bridges
due to wall ties

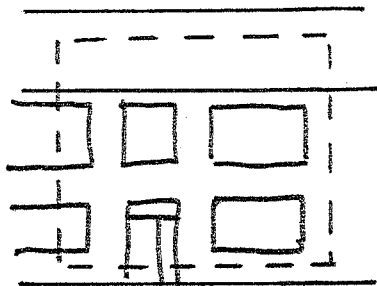
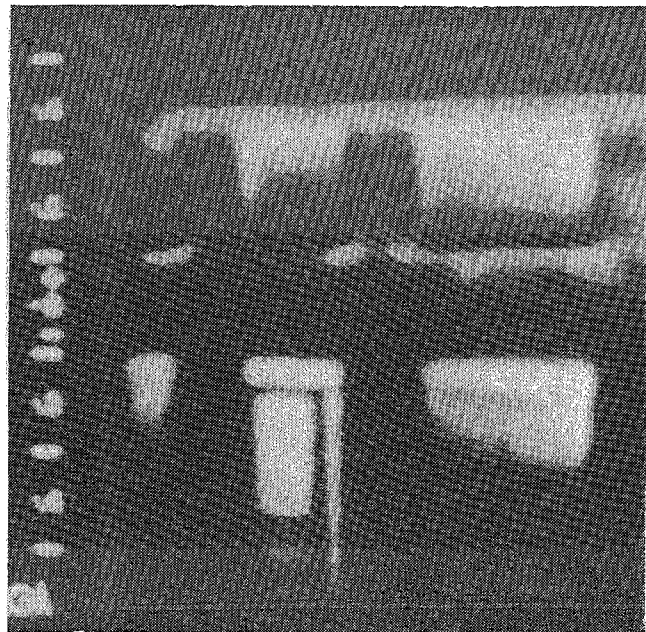


Figure 4.25

PENNYLAND AREA 2



Windows with insulating
shutters are darker (colder)
than uninsulated glazed door.

4.8 Weather Data

Weather data was measured at the Linford test house approximately 400 yards north-west of the Pennyland estate (see map figure 1.5). Measurements were made of air temperature, solar radiation on both horizontal and south-facing vertical surfaces, wind speed and direction.

Full details of the weather station will be found in the Linford project report. Details of the weather data for the monitoring period are given in Appendix 8.

In terms of air temperature and solar radiation, the weather over the main heating season used for energy assessment, October 1981 to April 1982, was fairly representative on average of a site in the south Midlands. There were 2269 degree days to base 15.5°C . This can be compared with 20 year average figures of 2030 degree days for the Thames Valley area, 2336 for the Midlands and 2289 for East Anglia (ref. 4.4).

The monthly mean solar radiation on the south-facing vertical surface was within 5% of the monthly means measured at Bracknell (100 km to the south). The weather over the period October 1981 to April 1982 was about 10% sunnier than the long term (1972-81) average.

The prevailing wind for the site was from the south-west with an average heating season wind speed measured at 10 metres height of 3.4 m/s.

Although the average weather data is fairly normal, the December of 1981 was exceptionally cold, with an average external air temperature of 0°C . There were arctic conditions for much of the month, with a minimum recorded temperature at Linford of -17°C . This has given an exceptionally good opportunity to test the comfort of the houses and the high degree of occupant satisfaction should be seen in the light of this extreme weather.

References

- 4.1 D.Etheridge, 'Leakage characteristics of houses at Great Linford, Report WH/T/R&D/81/96, British Gas Corp., 1981.
- 4.2 D.Etheridge, 'Neath Hill and Pennyland pressurisation tests', Watson House internal note (private communication), British Gas Corp., 1983.
- 4.3 Ventilation Measurements in Housing, P.Warren and B.C.Webb, C.I.B.S. 'Natural Ventilation by Design' Conference, Dec. 1980.
- 4.4 Degree Days, Fuel Efficiency Booklet No. 7, Dept. of Energy.

CHAPTER 5

PATTERNS OF ENERGY USE

- 5.1 Fuel Use and Costs
- 5.2 Statistical Presentation
- 5.3 Electricity Consumption
- 5.4 Cooking Gas
- 5.5 Water Heating
- 5.6 Space Heating Energy
- 5.7 Internal Temperatures
- 5.8 Energy Balances

This chapter looks at the basic fuel use of the various groups breaking it down into its main components, energy for lighting and appliances, cooking, water heating and space heating. Internal temperatures, both winter and summer are discussed and finally energy balances for each house type are produced.

5. PATTERNS OF ENERGY USE

5.1. Fuel use and Costs

The main aims of the Pennyland project are concerned with evaluating the changes in space heating energy requirements as a result of changes in insulation levels and passive solar design. In order to be able to estimate the changes in space heating it is necessary to have adequate knowledge about the other, non heating, uses of fuels. These are significant for several reasons.

First in order to relate metered fuel use to space heating requirements it is necessary to know what to subtract. This is especially important in the case of the passive solar investigation since, as pointed out earlier, what will be detected is a quantity of energy NOT used.

Secondly the non-heating fuel uses actually make a significant contribution to the space heating requirements through incidental gains. However the fraction of the fuel used which appears as incidental gains varies from one use of fuel to another - it is therefore necessary to know how much is used in each application. To this end the fuel uses involved, cooking, water heating and lights and appliances are treated in the following sections. Following a brief discussion of the overall energy consumption the section then proceeds to deal with the non-heating fuel uses in turn. The section on space-heating is somewhat longer because it turns out that the data measured with the heat meters is not sufficiently reliable. It is therefore necessary to make use of an indirect method of estimating the useful space heat energy. Finally there is then a discussion of the factors that are known to affect space heating consumption and the values for these in the different groups of houses. This latter discussion leads directly to the next main section on Analysis of Results.

Throughout this section and section 6 the energy consumption data described and discussed will be that recorded (or deduced) for a specific sample of houses on each estate. In order to carry out the analyses described in section 6 it is necessary that the houses involved should have fairly complete data sets over long periods of time. The conditions applied are satisfied by 14 houses on Neath Hill, 33 houses on Pennyland area 1 and 15 houses on Pennyland area 2. All the tabulated data applies to these sample groups unless specifically indicated otherwise.

Of course data exists for all the other houses in the experiment, and on some occasions it is appropriate to use this larger sample data. This

will be referred to in the text. However, it was found to be simply confusing to tabulate data for these varying sized samples since the numbers could not be compared from one table to the next.

The simplest comparison of fuel uses that we can make is that of annual gas and electricity consumptions for the various groups. For this purpose data has been used for as many five person houses from the four main project insulation groups as possible and also from a wider Milton Keynes survey of about 150 houses with similar heating systems, compiled in 1977. These last figures were gathered as background material for the Bradville solar house project primarily to see how 'typical' the house heat demand was. It seems reasonable to use the same data for this purpose in this project. The details of this material are discussed further in section 6.7.

The fuel costs have been worked out excluding standing charges and at Spring 1984 prices of 33.5 p/therm for gas and 4.99 p/kwh for electricity. These costs have been used in the evaluation of the Linford project and allow direct comparisons between them.

Table 5.1

	No. of Houses	DELIVERED ENERGY			
		Gas		Electricity	
		kWh/yr	£/yr*	kWh/yr	£/yr*
M.K. 4-Estate Sample (75/76 Data)	150	22172	253	2416	121
Neath Hill Uninsulated	18	23400	267	Not Measured	
Neath Hill Insulated	14	22480	256	3086	154
Pennyland 1	33	14010	160	2856	143
Pennyland 2	15	11530	131	2598	148

*Spring 1984 prices

In broad terms, the electricity use does not vary much between estates, but the gas consumption shows a large reduction with increasing insulation standard. The relative fractions of gas and electricity use also change considerably (see figure 5.1)

Perhaps the most important feature is that at the highest insulation levels, the annual expenditure on electricity is higher than on gas for heating. This suggests that further energy saving measures should perhaps be aimed at cutting electricity costs by measures such as small scale combined heat and power generation and the use of higher efficiency appliances.

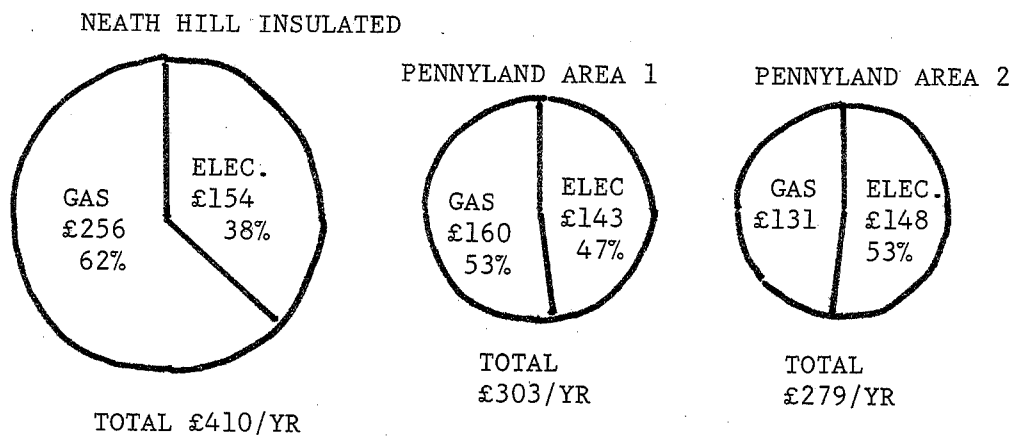
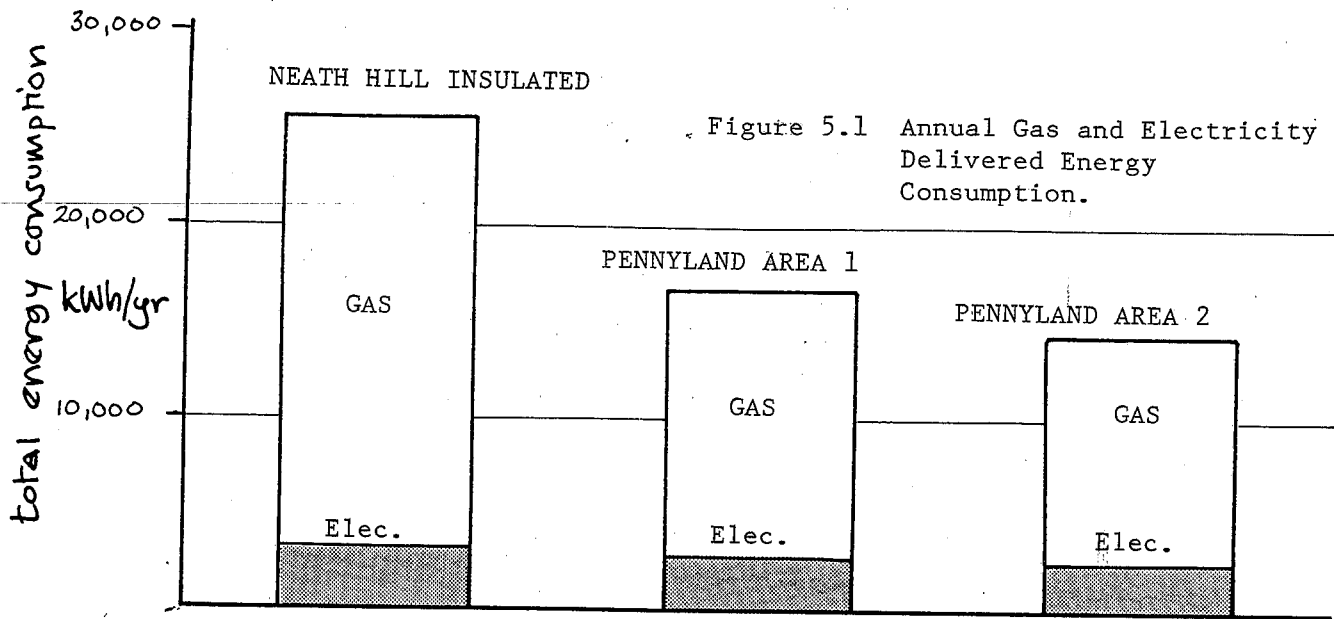


Figure 5.2 Percentages of fuel expenditure (excluding standing charges)

5.2 Statistical Presentation

Before embarking on more detailed group comparisons, it is necessary to explain some of the presentation that will be used, in particular the concept of a 'standard error' and the use of box plots.

5.2.1. Standard Error

Most of the comparisons in the rest of this report are in the form of a comparison of an average of one quantity with an average of another. By 'average' we mean the sum of the individual quantities divided by the total number. This is the 'mean' value. The box plots will use a different kind of average, the median.

Given the rather ragged spreads of consumptions that appear in this report (such as in figure 1.8), it is clear that it is rather uncertain whether the mean value of consumptions for the few houses actually monitored is really representative of a wider sample.

Graphs in Appendix 2 show how as the sample size is increased, the distribution becomes more bell-shaped or Gaussian, and we become more certain of the 'true' mean, i.e. what we would get if we had measured an infinite number of houses. Our uncertainty in detecting the true mean with a limited sample of houses is expressed as a 'standard error' or range within which there is a 68% probability that the 'true' mean actually lies. The 95% probability limits are at about twice the standard error range.

When we compare two uncertain means we produce a difference which also has an uncertainty. Hence the difference will also have a 'standard error' within which there is a 68% probability that the true answer lies.

It should perhaps be borne in mind that Gaussian statistics is derived from coin-tossing theory and gambling, and its applicability to housing experiments is not altogether clear. In this spirit, readers perhaps should look at some of the histograms in this report and ask themselves:-

- a) whether they are convinced that there is a difference between groups
- b) what money they would care to bet on how big the difference is.

5.2.2. Box Plots

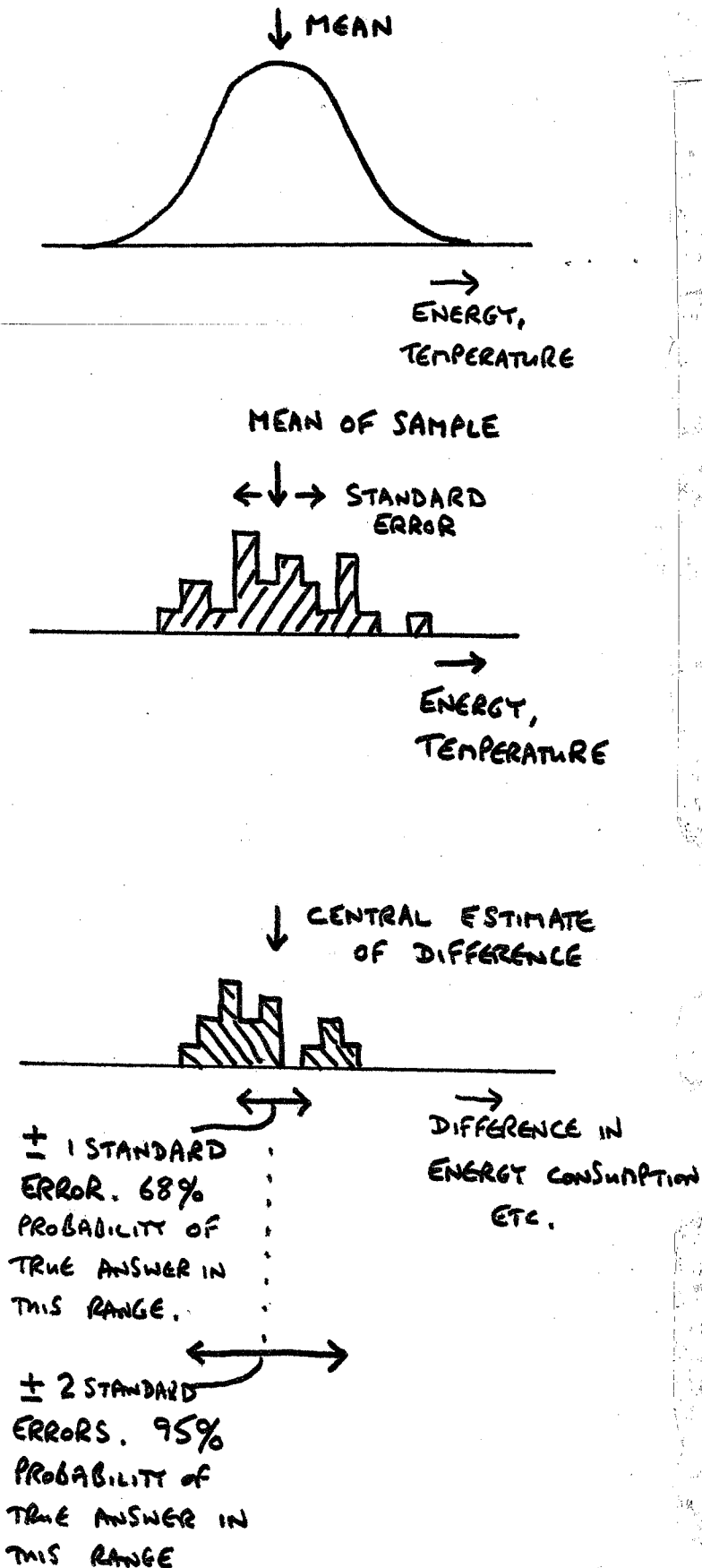
For many purposes, the complicated mathematics of standard deviations and errors are not required. For simple presentations of spreads of temperatures, the box plot has been used. This expresses the spread in terms of a 'median' or 'middle' value, the spread of the central 50% of values, and the total spread. This gives a simple picture of the total distribution, and is easy to work out:-

```

-----[  +  ]----- ← Upper limit of total spread
          ↑      ↑
          ↑      ↑ Upper limit of central 50% of values
          ↑      ↑ Median value

```

This is simply a method of presentation and does not give any meaning to differences.



IF WE COULD MEASURE A VERY LARGE NUMBER OF HOUSES WE WOULD GET A SMOOTH GAUSSIAN DISTRIBUTION OF ENERGY CONSUMPTIONS AND WOULD BE VERY CERTAIN ABOUT THE 'TRUE' MEAN.

GIVEN A LIMITED SAMPLE OF HOUSES, WE CAN ONLY WORK OUT A 'SAMPLE MEAN' AND A RANGE OVER WHICH THERE IS A 68% PROBABILITY THAT THE 'TRUE' MEAN LIES. THIS IS THE 'STANDARD ERROR'.

DIFFERENCES BETWEEN TWO RAGGED DISTRIBUTIONS ARE ALSO A RAGGED DISTRIBUTION.

THUS A DIFFERENCE BETWEEN TWO MEANS ALSO HAS A STANDARD ERROR AND A RANGE OVER WHICH THERE IS A CERTAIN PROBABILITY THAT THE 'TRUE' ANSWER LIES.

FIGURE 5.3

Figure 5.3

5.3 Electricity Consumption

Electricity is used for lights and appliances and in some houses for cooking. There is also likely to be some use of electric fires for space heating, but how much is unknown. Electricity consumption data has been analysed for a group of 14 Neath Hill insulated house, 33 Pennyland Area 1 houses and 15 houses on Pennyland Area 2. The electricity consumptions for these houses are shown in Table 5.2 below:-

Table 5.2. Electricity consumption figures (kWh/yr)

Site	Average consumption	Single aspect	Dual aspect
Neath Hill Insulated	3086±260*	-	-
Pennyland 1	2856±190	2900±250	2800±300
Pennyland 2	2598±170	3150±230	2200±130

* Standard error

These annual consumption figures should be compared with averages of 2416 kWh/yr for the 4-estate survey (see Table 5.1) and 3370 kWh/yr for the larger Linford houses.

It would appear from Table 5.2 that the Neath Hill houses have a larger electricity use than the Pennyland houses and that electricity consumption seems to fall as the insulation level is increased. This finding is not very statistically significant and it is difficult to find reasons why it should be so, especially since the 4-estate average is also rather low. There could be a lower use of extra electric fires for heating at Pennyland than Neath Hill. On balance it seems best to say that it is simply a statistical quirk due to lack of a large enough sample.

The Pennyland 2 single aspect houses also seem to have a high electricity consumption. Using both Pennyland 1 and 2 data, single aspect houses consume 300 kWh/yr (± 200 kWh/yr) more than dual aspect houses.

It might be thought that this difference is due to some change in electric lighting use due to the different house design. Electricity Council figures suggest that total annual lighting consumptions are typically only 360 kWh/yr (ref. 5.1), so this increase, if it is real is extremely large. Also, since on-peak electricity is about four times more expensive than gas, this apparent increase would have to be balanced by a compensating saving of more than 1300 kWh/yr of gas in order to save any money.

This illustrates the extreme difficulty of estimating any passive solar benefits. On balance, it seems safest to say that the apparent increase in electricity consumption is a statistical quirk. Statistically speaking, there is a one in ten chance that the real difference is zero or actually a decrease.

5.4 Cooking Gas

As noted in the previous chapter, all of the intensively monitored houses were equipped with an extra gas meter for measuring cooking gas consumption. Table 5.3 below shows the breakdown of gas use into cooking and boiler consumption for the three intensively monitored groups.

Table 5.3 Summary of cooking fuel use data
(kWh/yr)

Site	Average Total gas	Average. Boiler gas	Sample Average Cooker Gas	Percent with gas ckr.	Annual Gas per cooker
Neath Hill Insulated	22480	20660	1820	60	3000
Pennyland 1	14010	13300	715	55	1300
Pennyland 2	11530	10780	745	67	1120

There appears to be a significant difference in cooking gas consumption between Neath Hill and Pennyland. However, given the comments made in the previous chapter about the meter connection, this is rather uncertain.

The use of cooking gas at Pennyland appears to be rather lower than previous estimates, a figure of 2400 kWh/yr having been quoted by Uglow (ref. 5.2). Figures for electric cooking seem to be easier to obtain, a figure of 1190 kWh/yr having been produced by the Electricity Council (ref. 5.3). There is likely to be a 2:1 difference in gas cooking and electricity cooking energy consumption. For example the Linford data gives 755 kWh/yr for electric cooking (5 houses) and 1418 kWh/yr for gas cooking (2 houses).

It would thus seem that the Pennyland figures are reasonably credible, if a trifle low, while the Neath Hill figure is rather high. It seems unlikely that two groups of people would have such large differences in average cooking habits, even taking into account the slight demographic differences between the estates (see section 4.5).

It seems, therefore, that the apparent difference of 2000 kWh/yr in gas consumption is most likely to be due to measurement errors and for the later energy balances the Neath Hill cooking gas consumption has been taken to be 1200 kWh/yr. This is obviously a most unsatisfactory situation, since it creates yet another reason why the passive solar differences between Neath Hill and Pennyland, due to correct orientation, etc., cannot be resolved.

5.5 Water Heating

The level 3 monitoring installed on some Pennyland Area 2 houses and five of the Neath Hill insulated houses gives direct information about the useful energy supplied to the domestic hot water (D.H.W.) cylinder. The monthly consumption figures are set out in Table 5.4 and plotted in figure 5.4.

The hot water energy consumption varies over the year, peaking in December to February and with a minimum in June to August. This is due to the variation in ground and cold mains water temperatures (see Linford report). The most striking fact, though, is the large absolute difference between the Neath Hill and Pennyland data. This difference is statistically significant (standard errors on the data are about 100 mean watts or 4 kWh/day).

Table 5.4 Monthly variation of useful heat supplied to D.H.W.

Month	NEATH HILL INS.		PENNYLAND	
	Mean Watts	KWh/day	Mean Watts	KWh/day
Jan	655	15.7	392	9.4
Feb	672	16.1	359	8.6
Mar	726	17.4	361	8.7
Apr	576	13.8	357	8.6
May	488	11.7	309	7.4
Jun	457	11.0	275	6.6
Jul	445	10.7	276	6.6
Aug	461	11.1	269	6.4
Sep	493	11.8	253	7.8
Oct	581	13.9	327	7.8
Nov	655	15.7	350	8.4
Dec	691	16.6	371	8.9

The difference in annual useful energy between Neath Hill and Pennyland is large, 4630 kWh/yr for Neath Hill and 2610 kWh/yr for Pennyland. It seems that the bulk of this difference must be due to the slight demographic differences between the Neath Hill and Pennyland populations. The Neath Hill occupants have, on average, slightly larger families and an extra baby can make a lot of difference to the hot water consumption.

Monitoring differences, such as the slightly different positioning of the heat meters in the systems, or the use of 15 mm of polyurethane cylinder insulation, compared to a 25 mm mineral fibre jacket at Pennyland, could only account for about 15% of the apparent difference.

In addition to the direct measurements of water heating energy consumption estimates have been made from larger samples, including Pennyland Area 1 from summer boiler gas consumption and estimated boiler efficiencies.

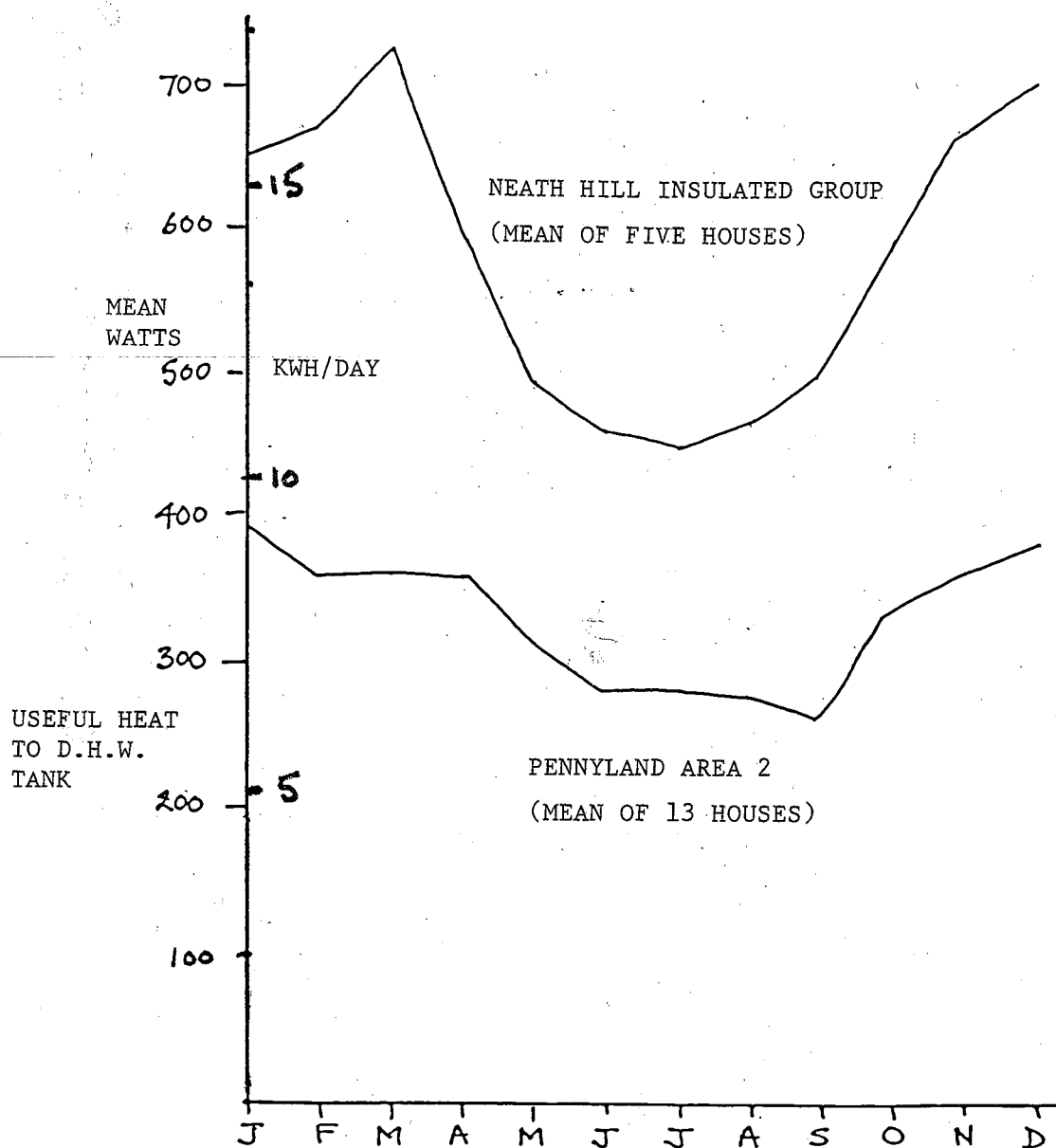


FIGURE 5.4 PENNYLAND AND NEATH HILL HOT WATER CONSUMPTION

The process involved will be described in section 5.6, but the results support the direct measurements very closely:-

Table 5.5 Comparison of measured and estimated useful heat to water heating:

	Direct Measurement kWh/yr	Calculated from Summer Gas Use kWh/yr
Neath Hill Ins.	4630	4310 \pm 460*
Pennyland Area 1	-	3250 \pm 240
Pennyland Area 2	2610	2640 \pm 300

* Standard error

By way of comparison, the hot water usage in the larger Linford houses averaged 3330 kWh/yr.

As with the case of cooking fuel use, there seems to be an unresolved problem. Do the Neath Hill inhabitants really use twice as much hot water as the Pennyland area 2 occupants, or is it just a fault of the monitoring system?

In this case, it seems difficult to find adequate explanations in terms of monitoring differences or minor differences in the heating system itself. There seems to be a distinct relationship between the length of occupation of an estate and its hot water use, which may have to do with the number of small children per household.

Correlations of hot water use with number of occupants have not produced any clear answers. This perhaps just serves to show our poor level of basic understanding about domestic energy use. We are never quite sure whether we are looking at differences in house design or in occupants.

For the purposes of further analysis, it has been assumed that the water heating difference between Neath Hill and Pennyland is real, but that the cooking consumption difference is a monitoring fault.

5.6 Space heating energy

In order to be able to relate the building design to the fuel used it is necessary to distinguish between the energy delivered to the house and that which makes a useful contribution to the heating requirements. The "delivered energy" is easy enough to measure, it is literally the energy measured by the gas and electricity meters. Of the energy used for heating only the fraction that appears in the hot water circulated to the radiators is counted as "useful". The heat which is lost from the boiler casing itself is counted in with the incidental gains if, as in the Pennyland and Neath Hill houses, the boiler is sited within the heated area of the house. What is required then, is an estimate of the change in the useful space heating requirements of the experimental houses.

In principle the space heating energy should have been monitored directly in all the houses monitored to levels 2 and 3 (about 64 houses in total). However, as indicated in section 4, the poor reliability of the heat meters (see for example figure 4.12) meant that this data base was not adequate for analysing space heating requirements. Instead a more roundabout route has been adopted for estimating the space heating requirements from the data that is actually available. This roundabout route uses the heat meter data to estimate the efficiencies of the boilers used at Neath Hill and Pennyland, and then uses the efficiencies in conjunction with the far more reliable gas-meter data to estimate space heating energy. The first step in this process is therefore to look at the boiler efficiencies.

5.5.1. Boilers and Heat Meters

As indicated in the discussion of the monitoring (section 4.3) a number of houses on Neath Hill and Pennyland 2 were monitored at level 3 so as to provide data on the performance of the boilers used on both estates. The level 3 monitoring involved two heat meters so that the total heat output of the boiler could be recorded. Although the availability of both heat meters was generally low there was sufficient data to analyse boiler performance. The basic method was to plot a graph of heat output against gas input for weekly data. An example of such a graph is shown in Figure 5.5. The weekly data points fit closely to a straight line which has a non-zero intercept on the gas input axis. The intercept can be interpreted as an effective standing loss from the boiler.

This standing loss is approximately half pilot light gas consumption and half various cycling losses. The slope of the straight line is the asymptotic efficiency of the boiler, i.e. the efficiency towards which the actual efficiency tends as the power output is increased. This is more obvious when the data is transformed to show the more usual plot of efficiency versus power output, as shown in figure 5.6.

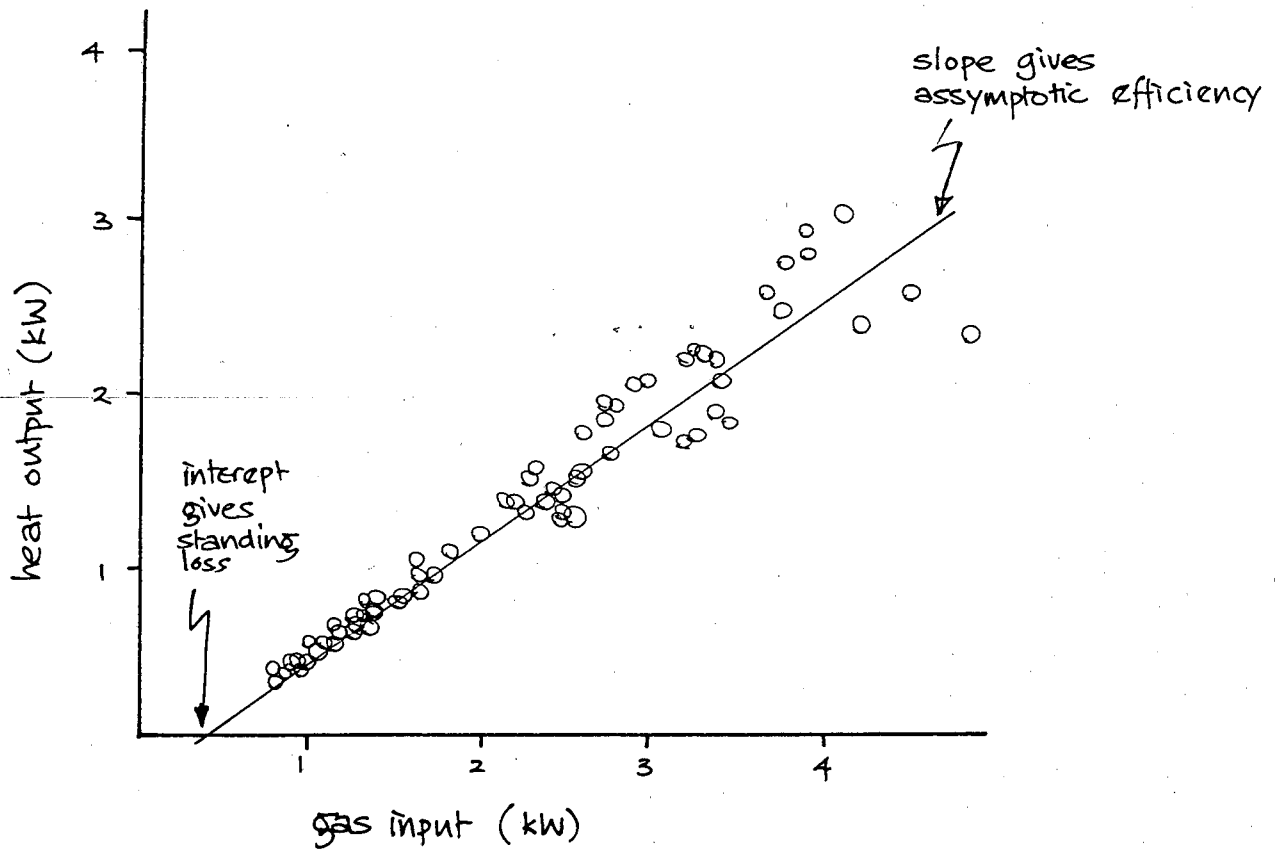


Figure 5.5 Boiler characteristic for a Neath Hill house

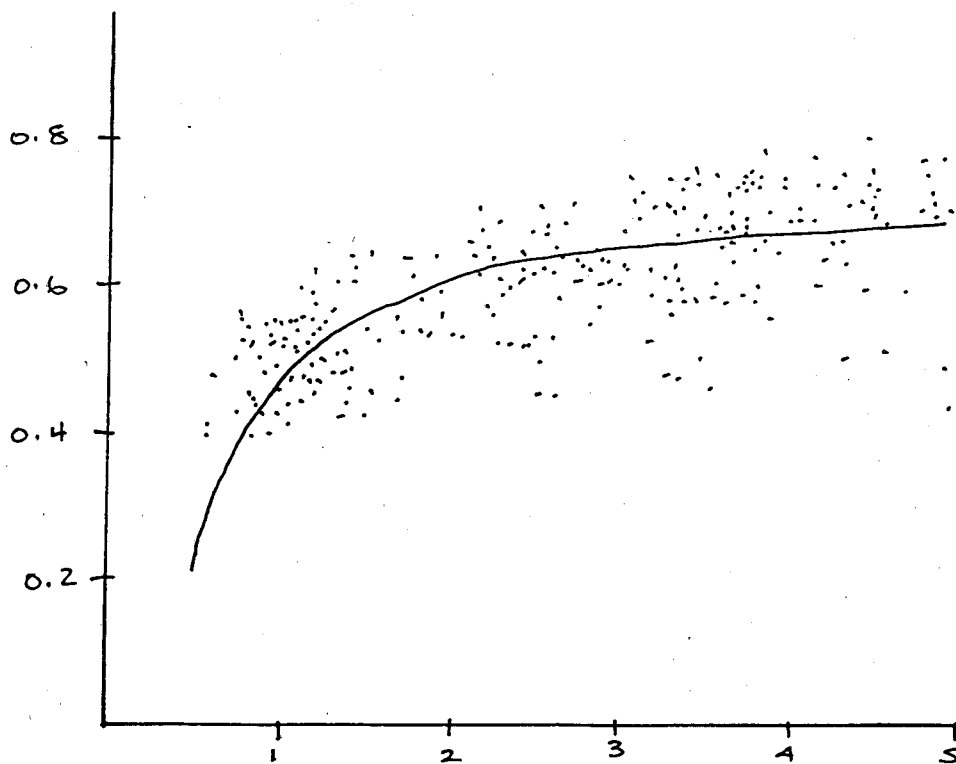


Figure 5.6 Part load efficiency curve for Neath Hill boiler
(a transformation of Figure 5.5)

Although these efficiency plots have been produced using weekly average data, similar plots were produced using daily averages in the Linford houses. Indeed, for a thorough description of the heating system performance using the low thermal capacity boilers, readers are referred to the Linford project report.

A more detailed presentation of the boiler calibration is presented in Appendix 10. There it is shown that for all the weekly data plots the correlation coefficients were close to 0.99, indicating a high level of confidence in the results. Less satisfactory is the fact that only a few of the heat meters had their calibration checked at the end of the monitoring period. For those that were checked the average calibration factor was 0.92 ± 0.03 . This error affects the slope of the boiler characteristic graph. The table below presents the results for the Pennyland and Neath Hill boilers with the calibration correction.

Table 5.6. Boiler characteristics for Pennyland and Neath Hill

Site	Standing loss (W)	Asymptotic efficiency	Full load calculated	Efficiency quoted
Neath Hill	355 ± 80	0.74 ± 0.01	0.73	0.74
Pennyland 2	230 ± 65	0.85 ± 0.04	0.83	0.82

Note that the errors quoted above are sample standard errors and do not include ranges of possible equipment errors, such as heat meter calibration errors and gas meter errors.

The agreement between the full load efficiency quoted by the manufacturer and that calculated from the derived characteristic gives some confidence to the results. They are also consistent with the results obtained at Linford and those reported by British Gas in their boiler measurements. The wide confidence band of our results should not however be overlooked.

One immediate result from this analysis is that there will be significant savings made at Pennyland due simply to the more efficient boiler. This is illustrated in Table 5.7 which compares the actual gas consumption (with an overall efficiency deduced from the boiler characteristic) with the gas consumption required in the other boiler to give the same heat output (together with the other boiler efficiency at this output). Thus the Table shows that had Neath Hill been fitted with a Pennyland boiler then the gas consumption would have been reduced by about 3400 kWh/yr.

The average efficiencies of the boilers can be deduced from the characteristic by working out the average input power (dividing the total consumption by the length of time) and then using this to calculate the average output power. The ratio of the two powers is the efficiency. Table 5.7 shows that whereas the actual Neath Hill boiler was operating at 62% efficiency the low thermal capacity boiler would have operated at an overall efficiency of 72% in the same house.

Table 5.7 Annual Boiler Efficiencies

Site	Neath Hill Boiler	Pennyland Boiler	Energy Saving kWh/yr
Neath Hill Ins.	62%	72%	3390
Pennyland 1	59%	69%	2790
Pennyland 2	56%	66%	2420

☐ Actual combinations

5.5.2. Estimation of Useful Space Heating Energy

The procedure used for estimating the useful energy used for space heating makes use of the following data;

1. the boiler gas consumption which is available for all houses
2. the boiler efficiencies deduced in the previous section
3. the limited data on DHW useful energy consumption documented in Table 5.4 and illustrated in Figure 5.4. This indicates a strong seasonality in the DHW useful energy requirement.

We can use the boiler gas and the boiler efficiencies to get a good estimate of the total useful output from the boiler. Now we require an estimate of the useful heat used for DHW for each house. This can be estimated by examining the boiler gas data for each house so as to deduce the gas used for DHW in the summer months (when the space heating requirement will be zero). The estimate of summer DHW gas is then used to get a useful DHW estimate for the summer. Assuming that the seasonality of the houses is all the same this can be used to estimate an annual DHW useful energy.

The entire procedure is illustrated in figures 5.7 and 5.8. Figure 5.7 starts with the weekly boiler gas consumption for a Neath Hill house. The summer period of June to mid-September when the gas consumption is almost constant, can be clearly distinguished. The weekly gas consumption can then be combined with the boiler efficiency plot to estimate the weekly useful boiler heat output.

In the next stage, in figure 5.8, the summer useful water heating consumption is extrapolated over the year using the seasonal variation measured in the limited sample of houses with full level 3 monitoring. This can then be used to estimate annual D.H.W. energy consumptions, and, by subtraction from the total useful heat output, the monthly variation in space heating consumption.

The main advantage of this method is that it can be applied to all the 5 person houses on Pennyland for which we have weekly data. The disadvantages of the method are that it requires far more numerical analysis and that it introduces unknown sources of error through the estimating procedures. For example it is not known to what degree the same seasonality factor will apply to all the houses, nor is it known how variable the boiler characteristics are. From the evidence available it seems that neither of these procedures will introduce errors as large as 10% (which is the uncertainty in the heat meter data).

One cross-check on the procedure used is to compare the estimates of total useful D.H.W. heat with those measured directly. This comparison, already presented in section 5.5, indicates a good level of agreement.

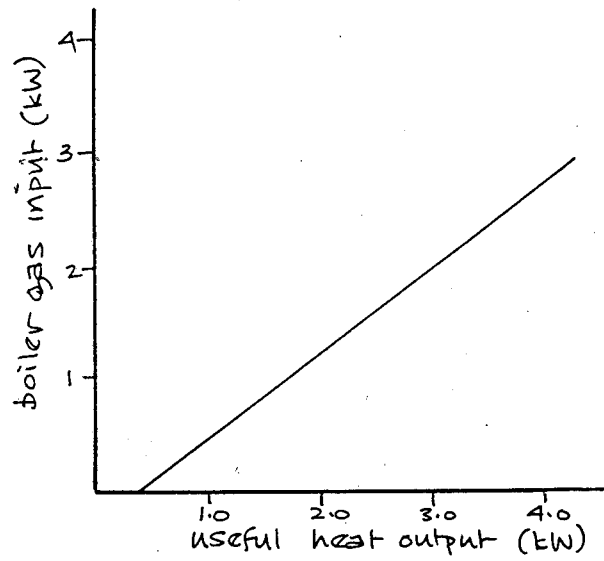
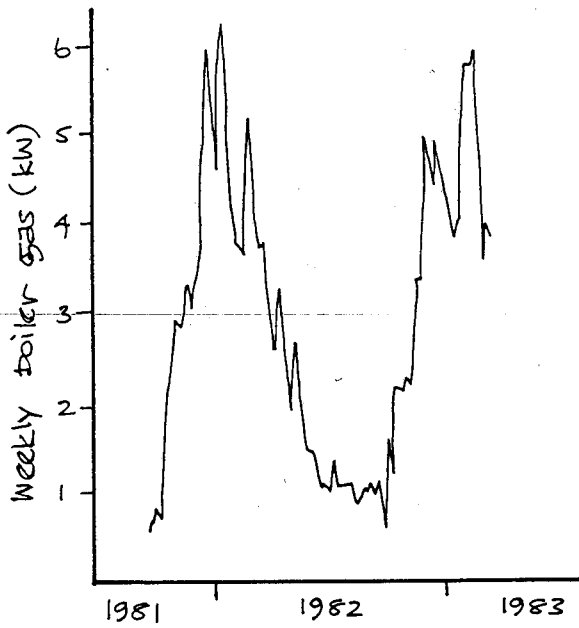
The final results, the figures derived for the useful space heating loads are set out in Table 5.8 below. It is this data that will be analysed in more detail in the next chapter.

Table 5.9 Useful Space Heating Energy

	kWh/yr
Neath Hill Insulated	8680
Pennyland 1 - Dual Aspect	6610
Single Aspect	6160
Pennyland 2 Dual Aspect	4670
Single Aspect	5070

The distributions of these space heating results are shown in figure 5.9. The energy difference between the Neath Hill and Pennyland Area 1 houses has decreased dramatically from that shown in the crude annual gas consumption figures in figure 1.8. We are now only dealing with useful space heating energies, the boiler efficiency savings having been removed by the estimation process.

These distributions will be refined further in the next chapter.



WEEKLY BOILER GAS INPUT X BOILER EFFICIENCY

WEEKLY BOILER HEAT OUTPUT

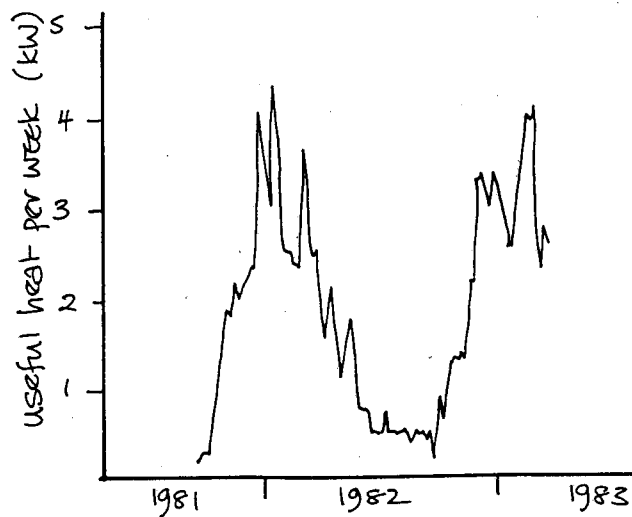
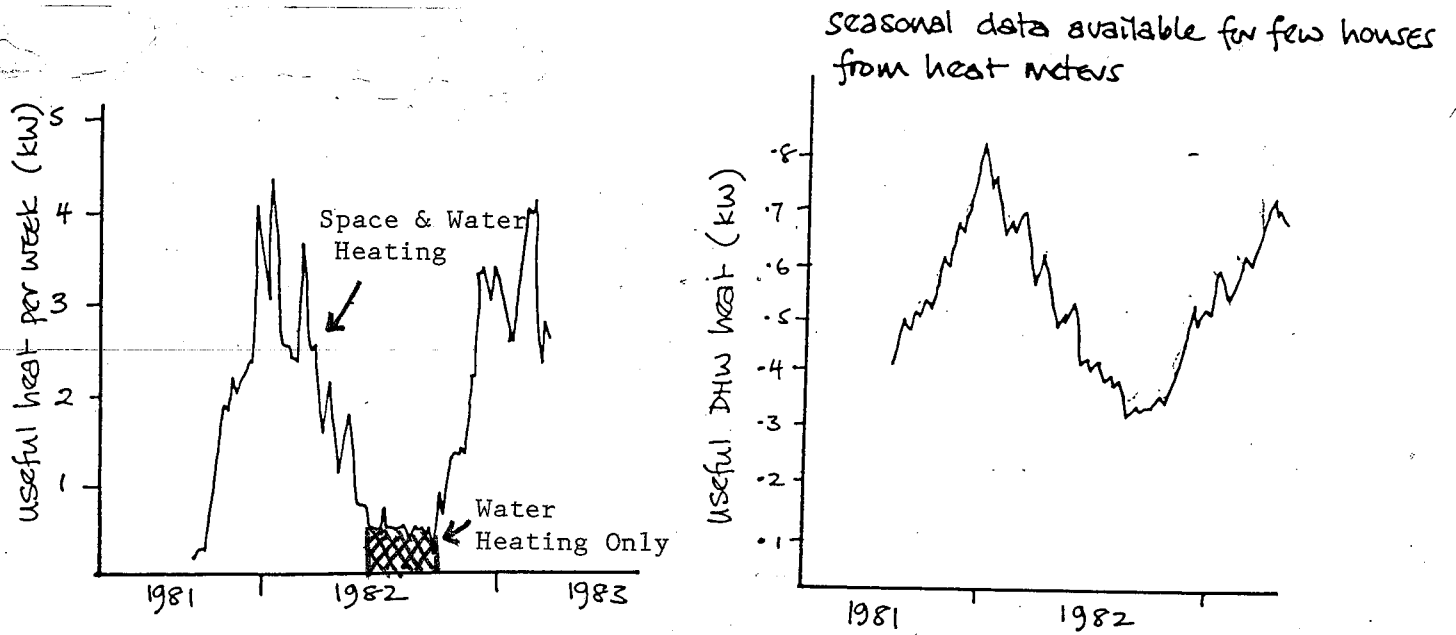


Figure 5.7 Illustrating the estimation of weekly useful heat output

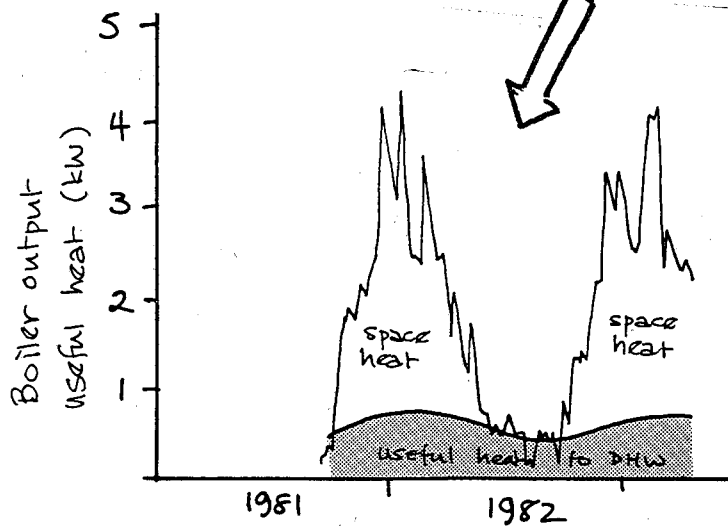
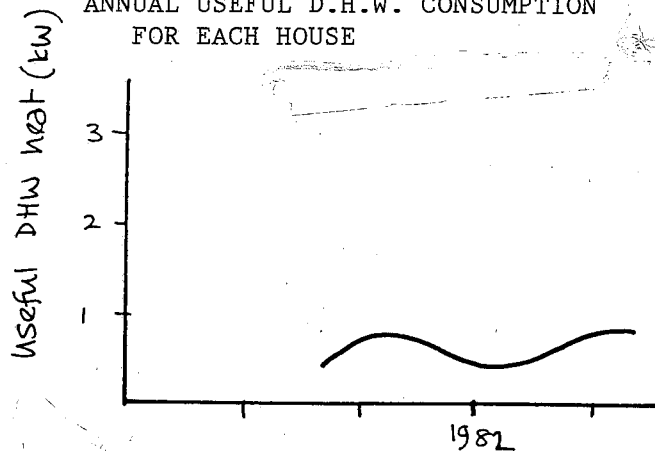


MEASURED SUMMER HOT WATER USE
FOR EACH HOUSE

X

SEASONAL VARIATION MEASURED
IN SMALL SAMPLE

ANNUAL USEFUL D.H.W. CONSUMPTION
FOR EACH HOUSE

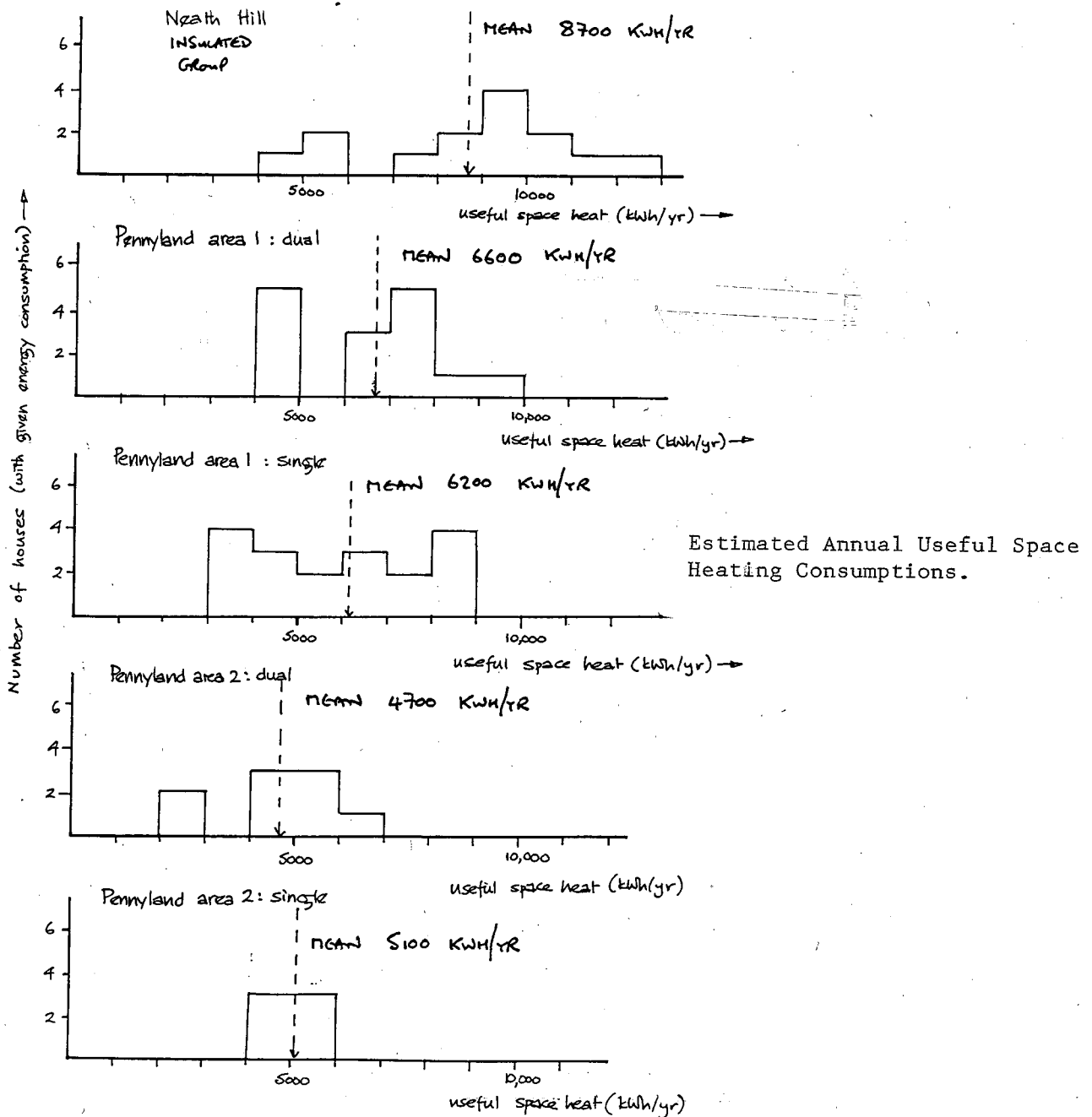
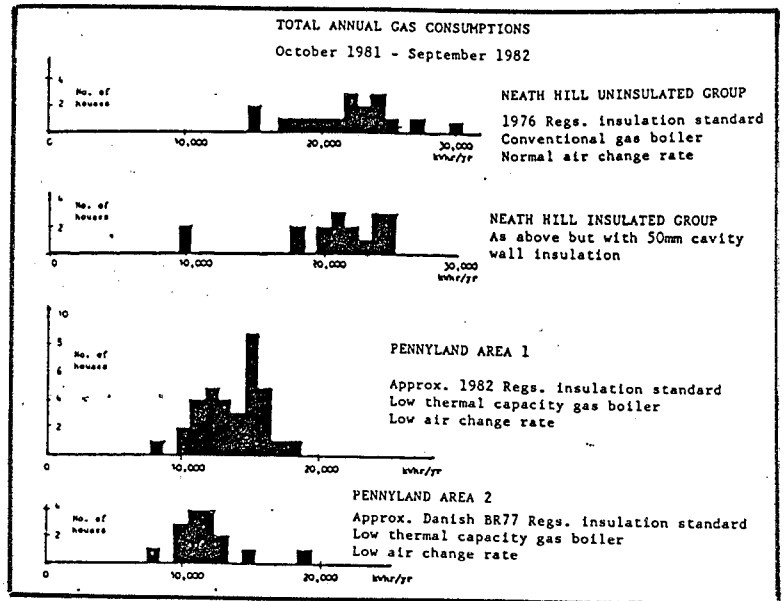


ALLOWS SPLIT OF TOTAL USEFUL
ENERGY FOR EACH HOUSE INTO
WATER AND SPACE HEATING

FIG. 5.8

Figure 5.9

Annual Total Gas Consumptions
(from figure 1.8)



5.7 Internal Temperatures

The D.T.I.'s have allowed the calculations of weekly average internal temperatures in the living room, kitchen and one bedroom for a large number of houses. We are interested in the heating season temperatures, both for their influence on space heating consumption and also as an indication of relative comfort conditions, both between groups in this project and for comparison with other field trials.

Another concern is peak summer temperatures. Summer overheating is a potential problem in passive solar houses and the need for extra thermal mass and/or summer shading devices can only be assessed by practical experience.

5.7.1 Heating Season Internal Temperatures

As indicated in the discussion of monitoring strategy, one of the major factors that causes identical houses to have very different space-heating fuel use is the temperature to which the house is heated. In the sort of houses being studied here a 1°C increase in the mean internal temperature will cause a 10-15% change in space heating energy, 1-2000 kWh/yr of useful energy or 1500- 3000 kWh/yr of gas. In other words a 1°C temperature rise is about equivalent to the maximum estimate of the benefit from the passive solar design. The variation in energy use as a function of temperature can be estimated using a simple monthly model of the house, the results are shown in Figure 5.10.

One of the difficulties that lies in wait for most energy saving schemes in houses is that almost any insulation or solar measure will cause an increase in average house temperature without any change in the occupants behaviour or thermostat settings. This inadvertent temperature rise occurs because the house will either get more heat input (in the case of solar designs) or take longer to cool down between heating periods (for better insulation), thus increasing the average temperature. The reason why this temperature rise causes difficulties is that it is not clear

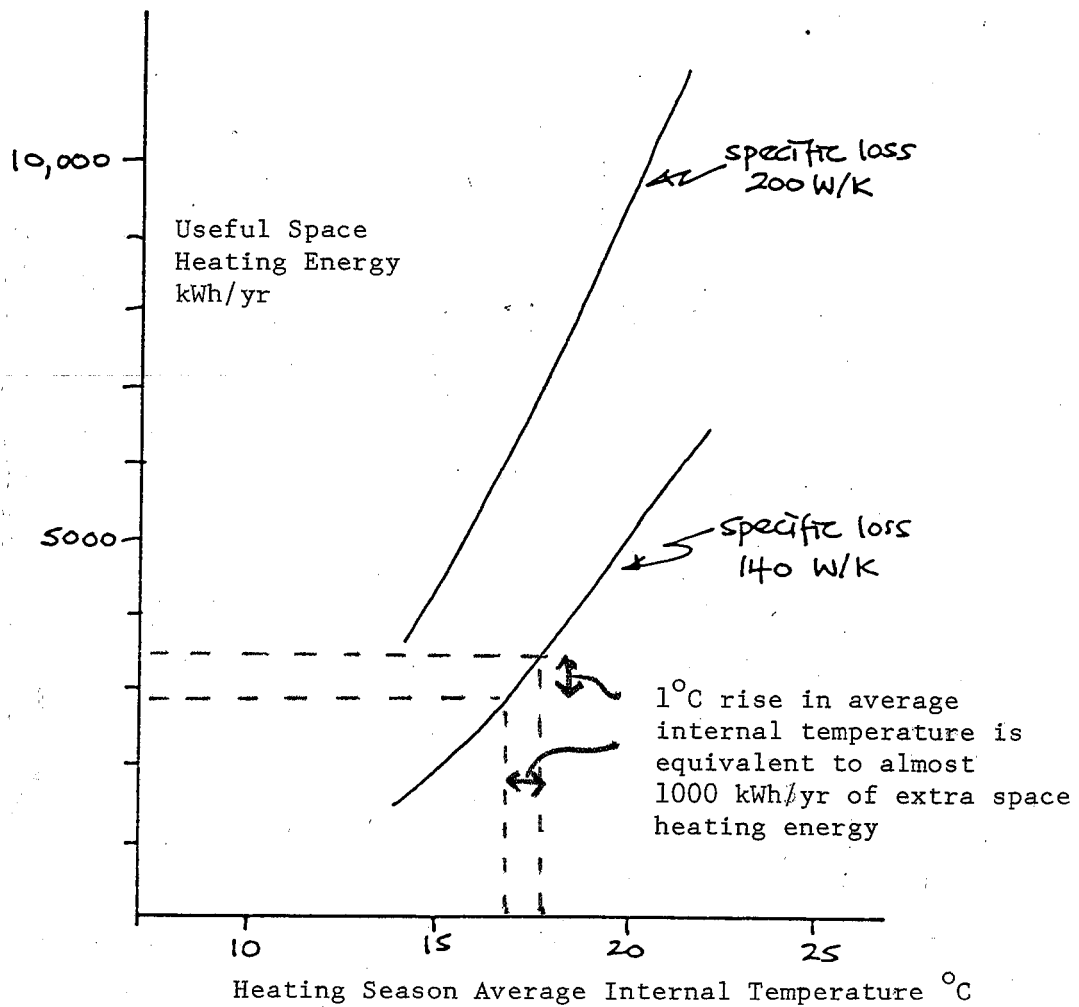


Figure 5.10 Effect of heating season average internal temperature on estimated space heating demand.

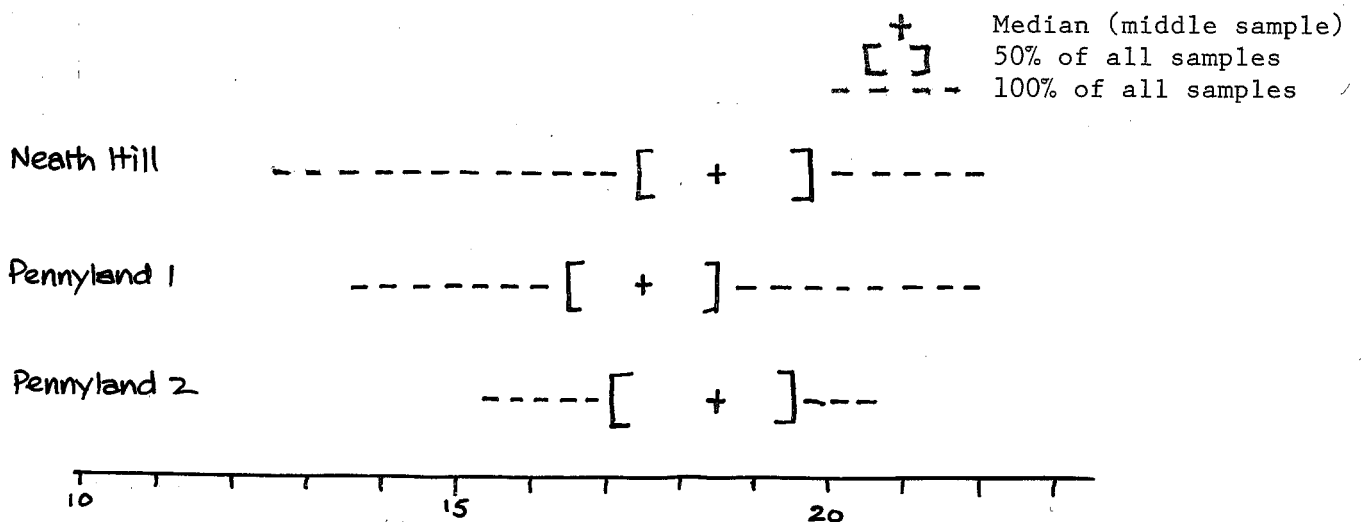


Figure 5.11 Measured heating season average internal temperatures (October - April).

whether or not the temperature rise should be counted as part of the benefit of the insulation or solar measures.

There are two arguments here. One is that the increase in average temperature actually gives benefits which the householder could have obtained by increasing the thermostat setting. Therefore when estimating the savings caused by a measure the energy use should be corrected to some standard average temperature.

The second argument begins by noting that the temperature rises caused by extra insulation and solar designs do not generally occur during the periods when heating is required - more often the average temperature increases because the temperature between heating periods is higher. Therefore this increase in temperature is not really "useful" to the householder and should not be taken into account when estimating savings. All that should be kept constant is the house temperature during the daily heating periods. At most there will be a small benefit due to a slightly higher house temperature at the beginning of each heating period.

In practice it is likely that the benefits lie somewhere between the two extremes. This discussion will be continued in the analysis of savings (Chapter 6). For the present we simply need to note that the temperature differences between the houses are potentially significant.

In order to make simple comparisons the house temperatures have been averaged over the heating season, defined as being October to April inclusive. The Differential Temperature Integrators record three temperatures, the lounge, kitchen and one bedroom temperature. The whole house temperature is defined as being

$$(\text{Lounge temp} + \text{Kitchen temp} + 2 * \text{Bedroom temp})/4$$

This is a volume weighted average though in practice the precise choice of weighting is relatively unimportant. The heating season, whole house average temperatures are set out in Table 5.10 and illustrated in Figure

Table 5.10 Heating Season Whole House Average Temperatures (Oct-Apr) °C

Site	Mean Temp.
Neath Hill Insulated	19.1
Pennyland 1 Total	17.8
Dual Aspect	17.0
Single Asp.	18.4
Pennyland 2 Total	18.4
Dual Aspect	18.0
Single Asp.	19.6

These results can be broken down room by room as shown in Table 5.11 and figure 5.12

Table 5.11 Heating Season Average Room Internal Temperatures °C

Site	Living Room	Kitchen	Bedroom
Neath Hill Ins.	20.3	19.9	18.1
Pennyland 1	19.1	19.5	16.4
Pennyland 2	19.4	19.7	17.7

The above figures show

1. high average temperatures in the living rooms with little variation between groups of houses.
2. higher bedroom temperatures in Pennyland 2 than Pennyland 1. This would be expected as one effect of the higher level of insulation.
3. higher bedroom temperatures in Neath Hill than Pennyland 1 or 2. This is probably due to the fact that several of the former houses have full central heating, with radiators in all bedrooms.

The figures for Pennyland can be broken down further, by solar variant. The effect of this is shown in table 5.12.

Table 5.12 Heating season room temperatures (°C)

Site	Living room single dual	Kitchen single dual	Bedroom single dual
Pennyland 1	19.9±0.4* 18.0±0.3	20.4±0.5 18.4±0.3	16.8±0.4 15.9±0.3
Pennyland 2	20.5±0.3 18.7±0.6	21.3±0.3 18.7±0.5	18.3±0.4 17.3±0.5

* standard error

LOUNGE

Neath Hill [+]

Pennyland 1 [+]

Pennyland 2 [+]

KITCHEN

Neath Hill [+]

Pennyland 1 [+]

Pennyland 2 [+]

BEDROOM

Neath Hill [+]

Pennyland 1 [+]

Pennyland 2 [+]

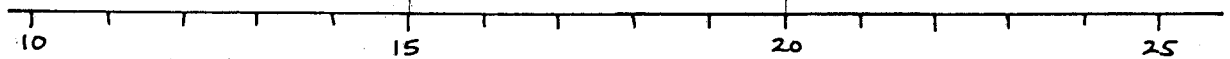


Figure 5.12 Box plots of heating season average room temperatures (Oct-Apr)

+ Median (middle sample)
 [] 50% of all samples
 - - - 100% of all samples

This table shows that the single aspect houses tend to have higher internal temperatures than the dual aspect ones. As pointed out in chapter 4, a part of this difference may be due to the different positioning of the external temperature sensor in the two types, but it is likely that there is some real internal temperature difference. This topic will be discussed further in the next chapter when the energy implications of the temperature rise are studied.

Finally, figures 5.13-15 show the monthly average whole house temperatures over the year for the three main groups. These show similar patterns with average temperatures in midwinter dropping to only 16-17°C, despite an average external temperature for December 1981 of about 0°C.

Although the total spreads in midwinter average temperatures are quite large, the spreads of the central 50% (in square brackets) are only 2-3°C, showing a considerable consistency of behaviour.

Comparison with other field trials

Table 5.13 below shows the heating season average whole house internal temperatures compared with the results from other field trials, including Linford.

HISTORY OF HOUSE AVERAGE INTERNAL WINTER TEMPERATURES IN
POST-WAR FIELD TRIALS

	Year	Low	Average	High	No of Houses	Insulation Level	Ref.
1	48-49		12.2-16.3		36	Low	5.4
2	49-50		12.0-17.5		36	Low	5.4
3	49-50	12.4	13.2	14.2	259	Low	5.5
4	69-73		17.0-19.5		60	Med-High	5.6
5	71		18.0-19.0		10	Med-High	5.7
6	74	13.1		14.7	25	Med-High	5.8
7	77		16.3-16.7		11	High	5.9
8	78		15.6		24	V. High	5.9
9	77	12.7	14.6	17.1	12	V. High	5.10
10	81/82		19.1		17	Med-High	Neath Hill
11	81/82		17.8		37	High	Pennyland 1
12	81/82		18.4		18	V. High	Pennyland 2
13	82/83	16.3	18.6	20.1	6	V. High	Linford

The results show that the Pennyland and Linford measurements are amongst the highest in the historical record, showing a strong tendency to whole house heating. They also show that the low energy consumptions have not been achieved by low internal temperatures and poor comfort conditions, rather, the reverse is true.

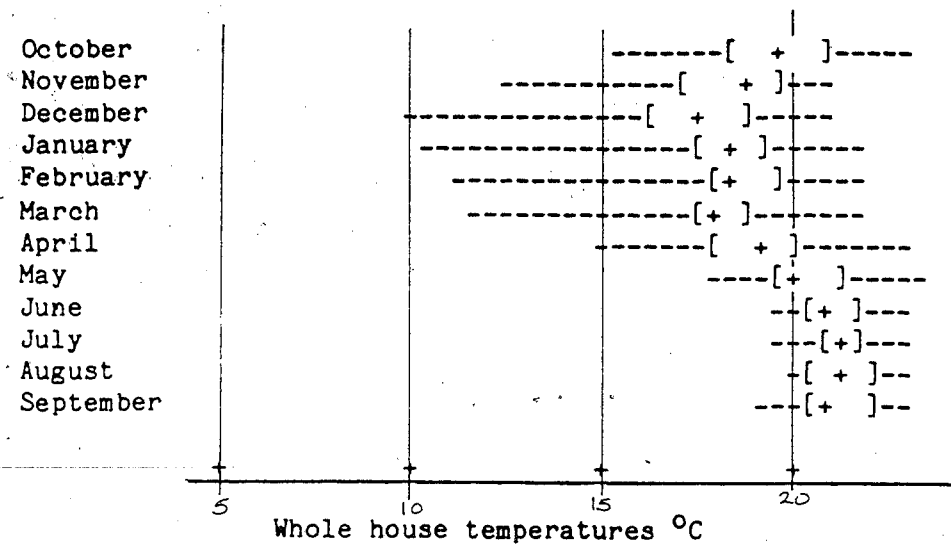


Figure 5.13 Box plots of Neath Hill monthly average internal temperatures

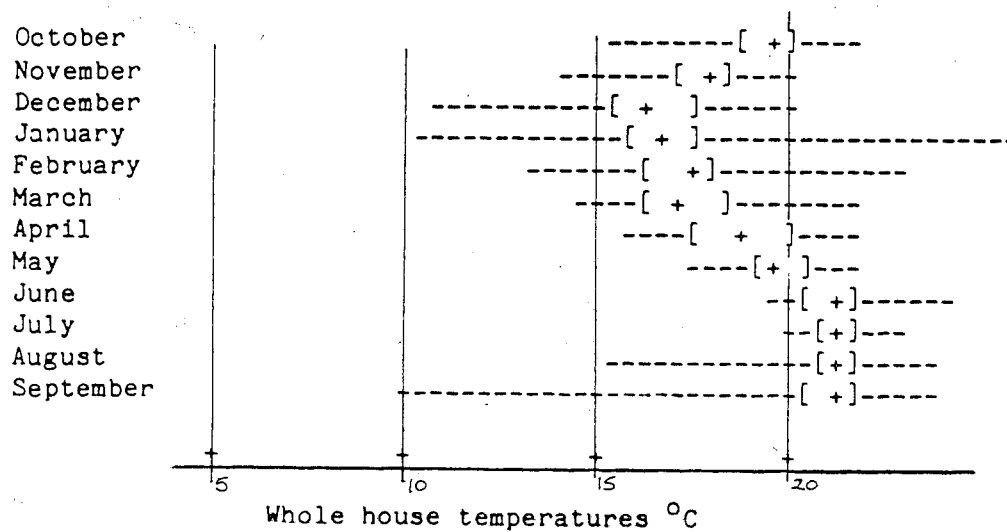


Figure 5.14 Box plots of Pennyland 1 monthly average internal temperatures

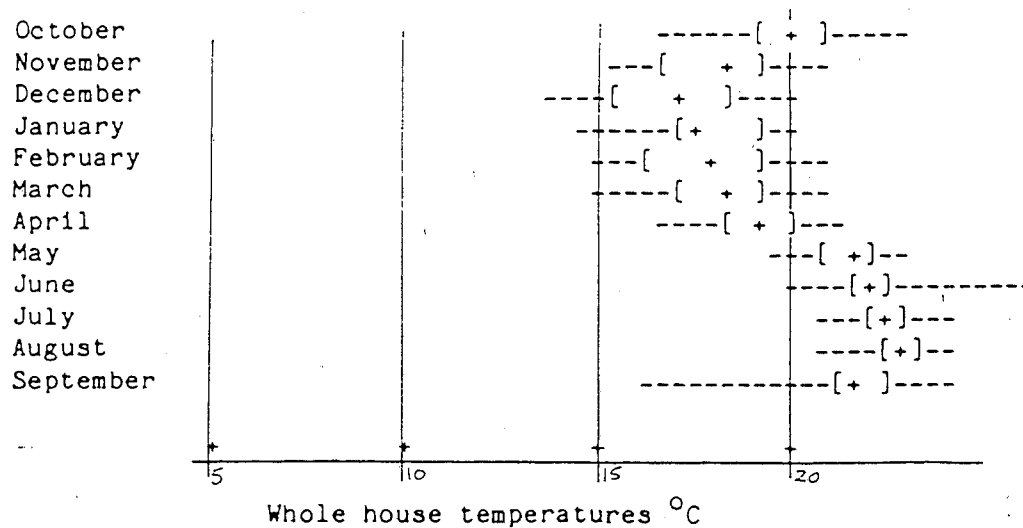


Figure 5.15 Box plots of Pennyland 2 monthly average internal temperatures

5.7.2 Summer House Temperatures

Although not directly related to winter space heating consumption, the topic of summer peak temperatures should be reported at this point. With the large glazing areas of the Pennyland houses, the possibility of summer overheating was a serious concern, especially since the Bradville solar house had managed to produce a newspaper headline 'COUPLE ROAST IN SOLAR HOUSE'. It was later conceded that the solar house was actually no hotter than the non-solar one next door.

Summer average temperatures do not seem to have varied much from house to house, or group to group. Table 5.14 below shows whole house average temperatures for May to September 1982.

Table 5.13 Summer whole house average temps. (May-Sept) °C

Neath Hill Ins.	21.6 ± 0.2
Pennyland 1	21.3 ± 0.1
Pennyland 2	22.2 ± 0.2 *

*Standard error

These figures are also shown in figure 5.16. The central 50% figures are perhaps more important than the total spreads, since the D.T.I.'s tended to be at their lowest level of reliability during the summer due to flat batteries.

The results show about 1°C average increase in temperature due to the increased insulation in Area 2.

A more important matter is the absolute summer peak temperature. Two surveys were carried out, sampling instantaneous internal temperatures using the D.T.I.'s. The most thorough survey was carried out on July 13th 1983, between 4.00 and 5.30 p.m. on one of the hottest days of the year. The air temperature at the time was about 29°C. The day had full clear sky radiation and was preceded by several similar days

Histograms of room temperatures for 5 groups of houses are shown in figure 5.17 and average values are given below:

Table 5.14 Spot summer internal temperatures (°C)

	No. of houses	Living room	Kitchen	Bedroom
Neath Hill	10	26.6	26.5	27.0
P1 dual	5	26.0	27.1	28.0
P1 single	4	26.6	27.1	26.6
P2 dual	5	26.1	27.0	27.1
P2 single	3	27.5	27.6	28.0

Given the basic measurement accuracy of the DTI of about ±1°C and the within group spreads of temperatures, it cannot honestly be said that there is any major difference in temperatures between groups, certainly not greater than 1°C.

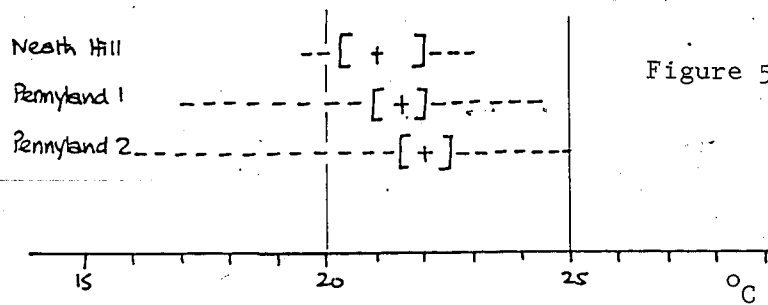
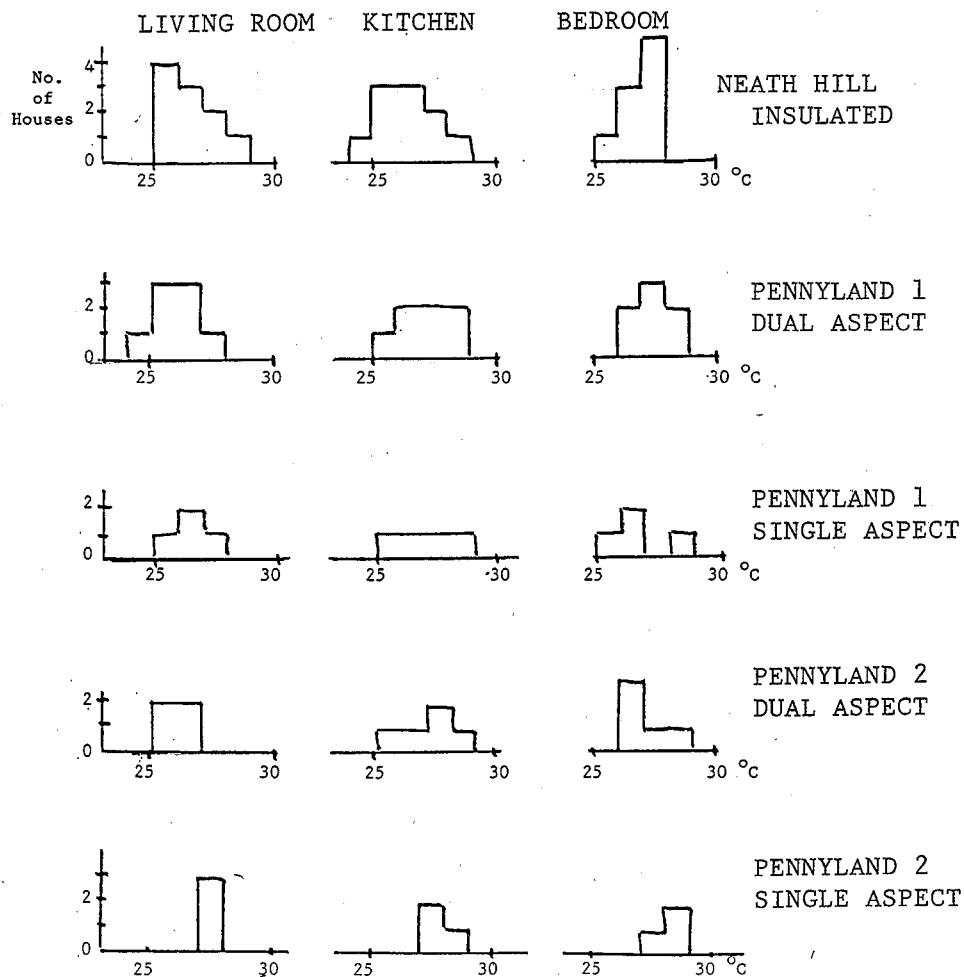


Figure 5.16 Average Summer Internal Temps. (May - Sept)

Figure 5.17 Overheating Survey July 13th 1983



Spot Room Temperatures 4-5.30 p.m.
 External Temperature approx. 29°C

Measurements in the Linford occupied houses at the time showed that the peak internal temperatures remain below the peak external temperature (see figure 5.18). This shows how the thermal mass of the house and the good insulation smooths out the large diurnal swings in outside air temperature.

The lack of a large difference between peak temperatures at Neath Hill and Pennyland 1 suggests that the extra thermal mass of the Pennyland design is not really necessary and that medium weight construction, as used at Neath Hill is adequate.

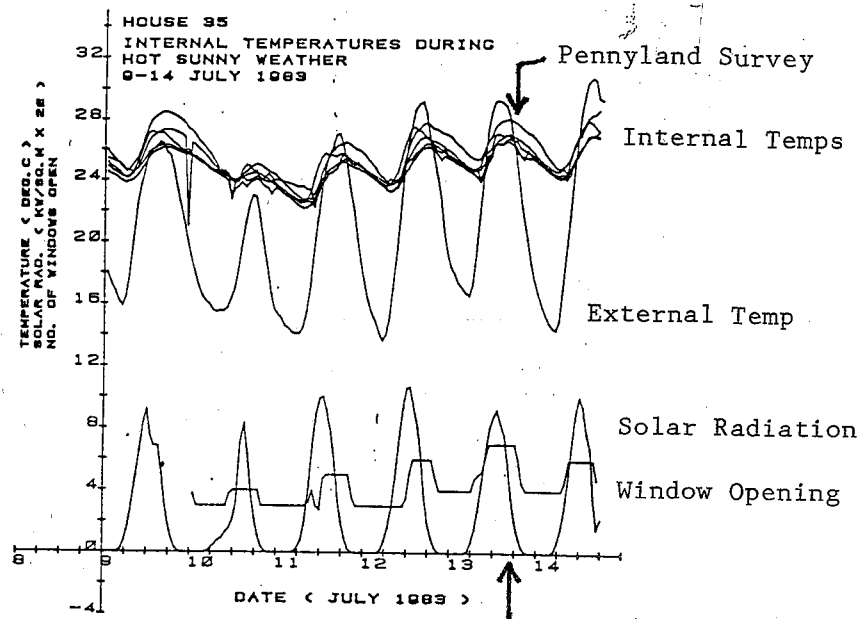


Figure 5.18 Sample Temperature Data from a Linford House Showing Internal Temperature Variations at Time of Pennyland Overheating Survey.

5.8 Energy Balances

In order to illustrate the energy flows through the various house designs, we can build up individual energy balances of the form:-

$$\begin{array}{ccccccc} \text{Boiler + Incidental + Solar} & = & \text{Fabric + Ventilation + D.H.W. + Flue} \\ \text{Gas} & \text{Gains} & \text{Gains} & \text{Loss} & \text{Loss} & \text{Loss} & \text{Loss} \end{array}$$

The various components have been estimated as follows:-

Boiler Gas

As measured by gas meters, i.e. total gas - cooking gas.

Incidental Gains

These are assumed to be made up of boiler casing heat losses, amounting to 5% of the boiler gas input, 100% of the house electricity use, 10% of the hot water use plus an allowance of 40 watts continuous for hot water cylinder losses and an average of 125 watts continuous for occupant body heat.

Solar Gains

These have been estimated on the basis of equivalent solar apertures calculated by regressions relating house space heating consumption to external temperature and solar radiation, as described in section 6.3.2.

Fabric Loss

This has been calculated on the basis of individual house descriptions and theoretical U-values from the I.H.V.E. Guide.

Ventilation loss

This has been left as a remainder of the other terms. As will be shown in section 6.4.1, the values are on average consistent with those determined from pressure test results, but with rather large month-to-month variations due to the cumulative errors in all the other energy terms.

D.H.W. Loss

This has been calculated from summer gas consumption, as described in section 5.6.

Flue loss

This has been worked out using the sample boiler efficiencies worked out using heat meter information, as detailed in Appendix 10.

5.8.1 Delivered Energy

We can plot these various energy components in different ways, both on a monthly basis and an annual one. Figure 5.19 and Table 5.15 below summarise the measured energy consumptions for the intensively monitored groups.

Table 5.15 Summary of Energy Use of Main Groups

House Group	No. of Houses	DELIVERED ENERGY				USEFUL	
		Total Gas kWh/yr	Boiler Loss kWh/yr	Gas Cooking* kWh/yr	Electricity \$ kWh/yr	Space Heating kWh/yr	Water Heating kWh/yr
NEATH HILL INSULATED	14	22480	7670	3000	3090	8680	4310
PENNYLAND 1	33	14010	3700	1300	2860	6350	3250
PENNYLAND 2	15	11530	3320	1120	2600	4830	2640

*Average for houses with gas cooking

\$ Average for all houses.

This table clearly shows the energy savings between the groups. Figure 5.19 shows that the reduction in energy use is far greater than just the reduction in useful space heating. The improvement in boiler efficiency between Neath Hill and Pennyland cuts the flue losses dramatically. In fact the Neath Hill flue losses are sufficiently large to supply all the space and water heating requirements for a Pennyland Area 2 house!

5.8.2. Heat Losses

These have been worked out on a purely theoretical basis but as will be shown in section 6.3.3 there seems no reason to think this seriously in error. Full details of house fabric heat losses will be found in Appendix 4.

Using ventilation rates worked out from pressure test results (see section 4.6 and Appendix 7) the various proportions of house heat loss attributable to different routes can be worked out. Figure 5.20 shows these proportions as pie charts for dual aspect houses ranging from the Neath Hill uninsulated level to the Pennyland Area 2 level insulation standard.

This shows clearly that the ventilation rate term which was thought might dominate the energy loss of a low energy house design has remained a fairly small proportion of the total loss across the whole project. This is due to the good airtightness of the Pennyland houses, which has reduced this term in line with the reductions in fabric heat loss.

Figure 5.19 Delivered Energy to Neath Hill Insulated and Pennyland 5 person houses

Sept 81 - August 82

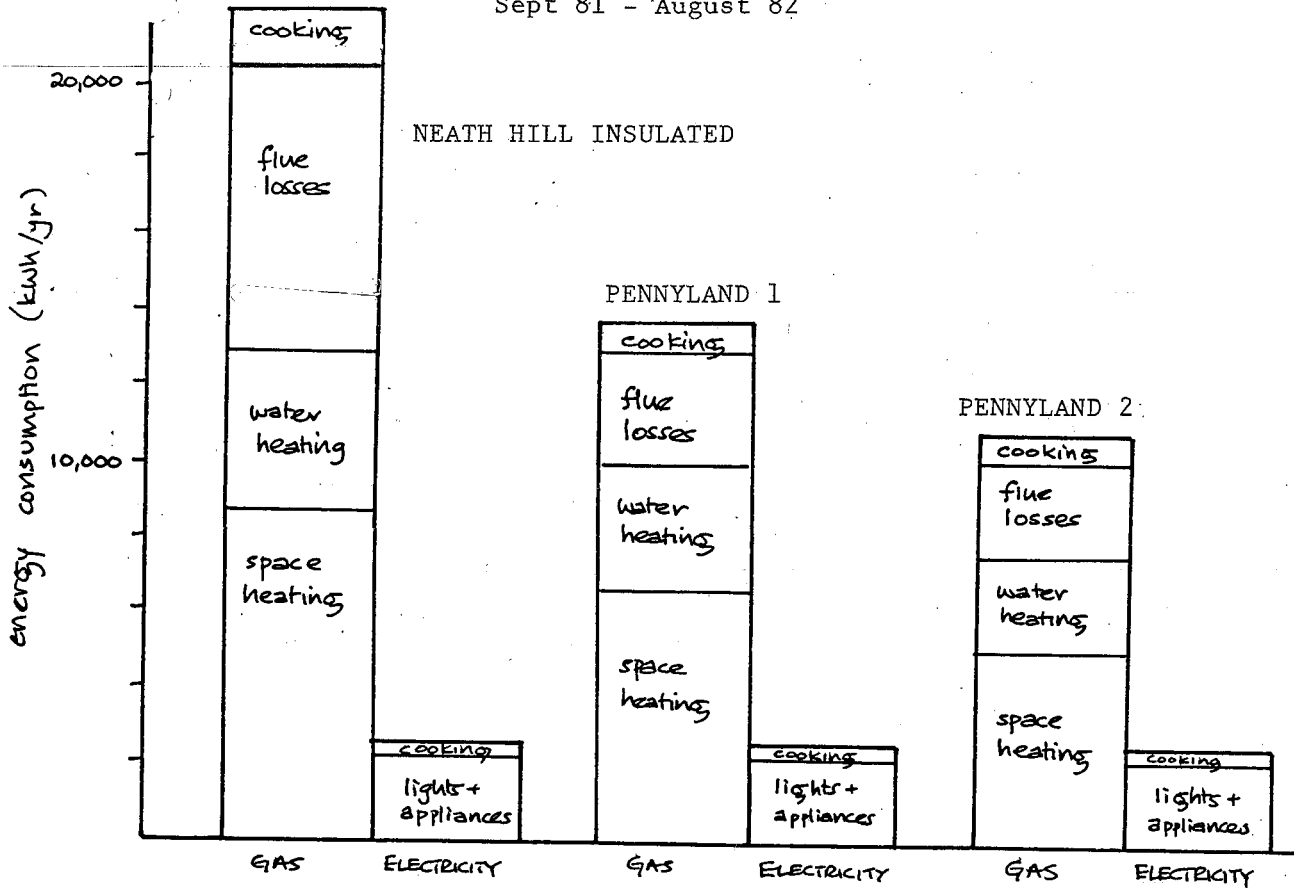
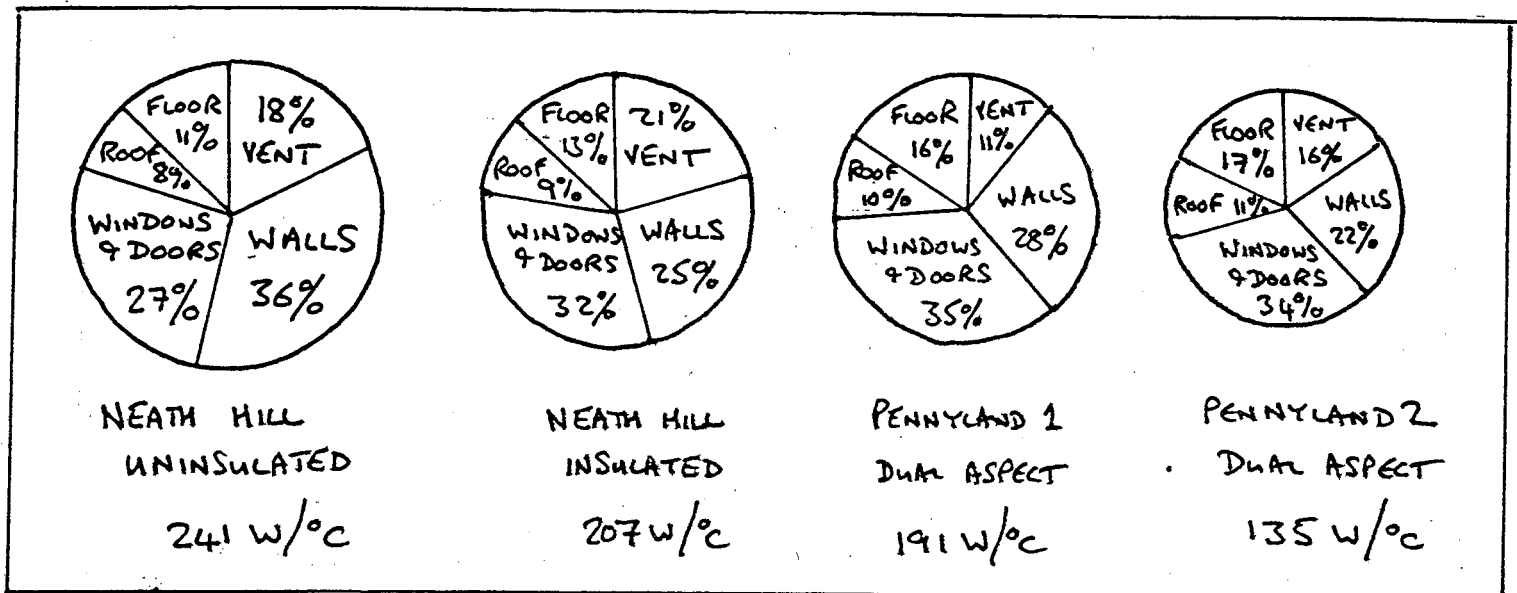


Figure 5.20 Heat Losses from End-of-Terrace Dual Aspect Houses



5.8.3. Balancing the energy flows

Using the separate energy estimates we can first build up a month-by-month gross heat loss for the house, i.e. $\sum U.A + C_v \times \text{measured } \Delta T$. This is then 'filled up', first with incidental free heat gains from cooking, lights, etc, then solar gains and finally space heating energy.

Plots of monthly energy balances for the Neath Hill Insulated house type and the two Pennyland Area 2 types are shown in figure 5.21. This clearly shows the large decrease in both gross heat demand and space heating as the insulation level is improved.

Plots for the Area 1 houses and the full monthly numerical tables will be found in Appendix 11.

The free heat gains tend to peak in mid-winter, since they contain a boiler casing heat loss term which is proportional to the amount of gas burnt (see Linford report for a detailed breakdown of incidental gains). The higher overall energy consumption of the Neath Hill houses means that they have higher free heat gains than the Pennyland Area 2 houses.

The solar gains are largest in the single aspect house type, though this also has a higher gross heat loss than the dual aspect type at the same insulation level, leading to similar auxilliary space heating consumptions.

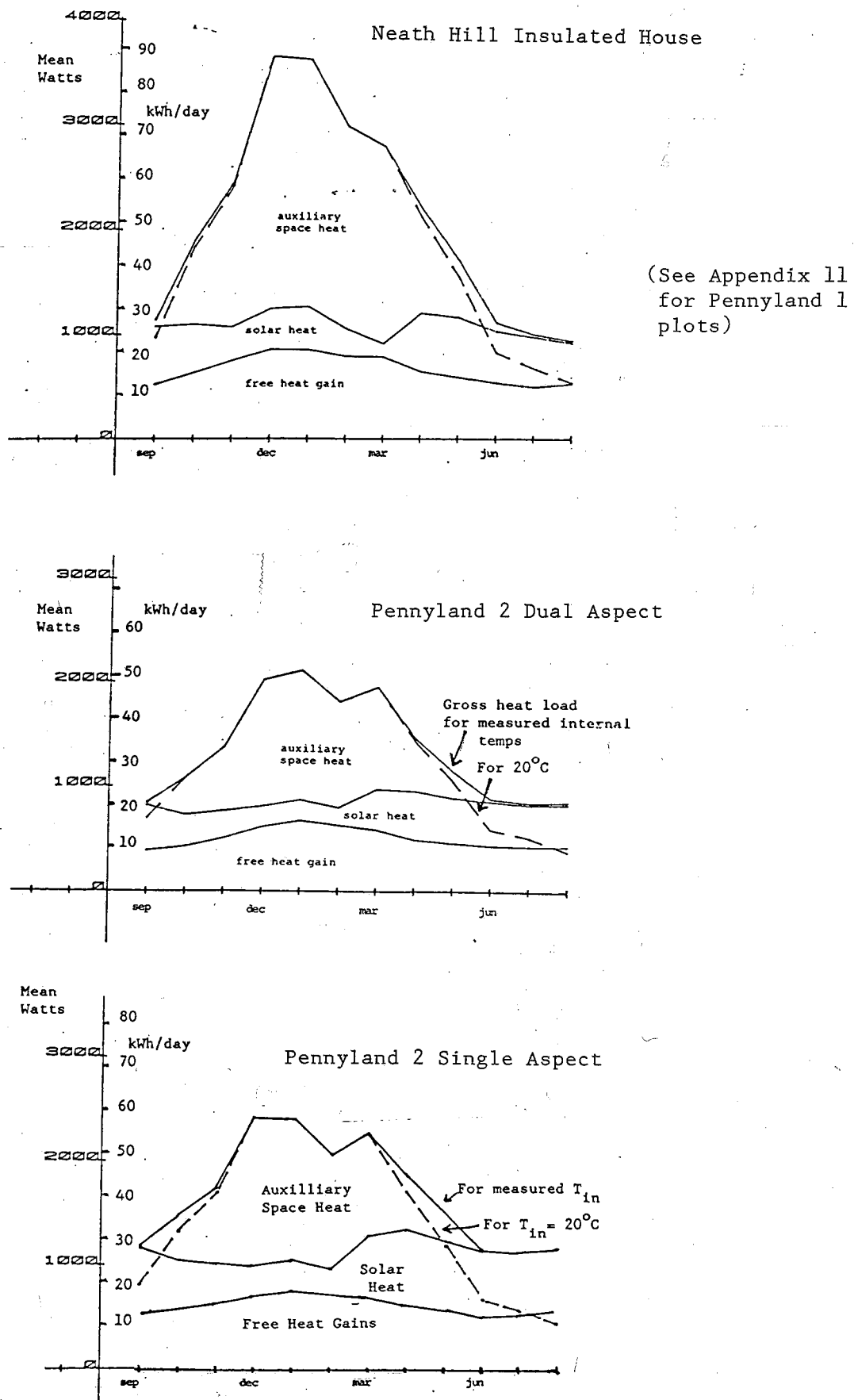
When we come to total the various combinations over the year, we have to draw a distinction between heating necessary to maintain a desired comfort level and unnecessary heat inputs that overheat the house or are vented away in summer. To this end an 'adjusted' gross heat loss has been calculated using measured internal average temperatures where these are less than 20°C and a cut-off value of 20°C in summer (dotted line in graphs). This means that most of the summer solar gains are not deemed to be useful for space heating purposes.

Table 5.16 below gives the adjusted gross heat loss figures for the various groups and the absolute solar contributions to space heating. As explained in chapter 2, this solar contribution does not imply any space heating energy difference between house designs. That is the 'marginal' solar energysaving, and will be dealt with in the next chapter.

Table 5.16 Adjusted Gross Heat Losses and Absolute Solar Gains

House Type	Adjusted Gross Heat Loss kWh/yr	Absolute Solar Gains kWh/yr
Neath Hill Insulated	16,500	1770
Pennyland 1 Dual Aspect	14,100	2230
Pennyland 1 Single Aspect	14,500	2300
Pennyland 2 Dual Aspect	11,100	1930
Pennyland 2 Single Aspect	12,900	2300

Figure 5.21 Monthly Energy Balances



It should be stressed that these are measured results and thus the differences in gross heat loss reflect not only differences in $\sum U.A + C_v$, but also differences in measured internal temperatures.

Figure 5.22 shows annual proportions of free heat gains, solar heat and auxiliary heating to the adjusted gross heat loss for the year. This clearly shows that as the standard of insulation is improved the house becomes predominantly heated by the solar gains and free heat gains, with the space heating mainly acting to 'top up' the balance.

Measurements in the Linford houses have studied this process in detail. From these results, it has been observed that the space heating system is mainly used for bringing the house up to temperature in the morning. Solar gains carry most of the heat load during the day and incidental gains, which tend to peak in the evening, heat the house through to midnight.

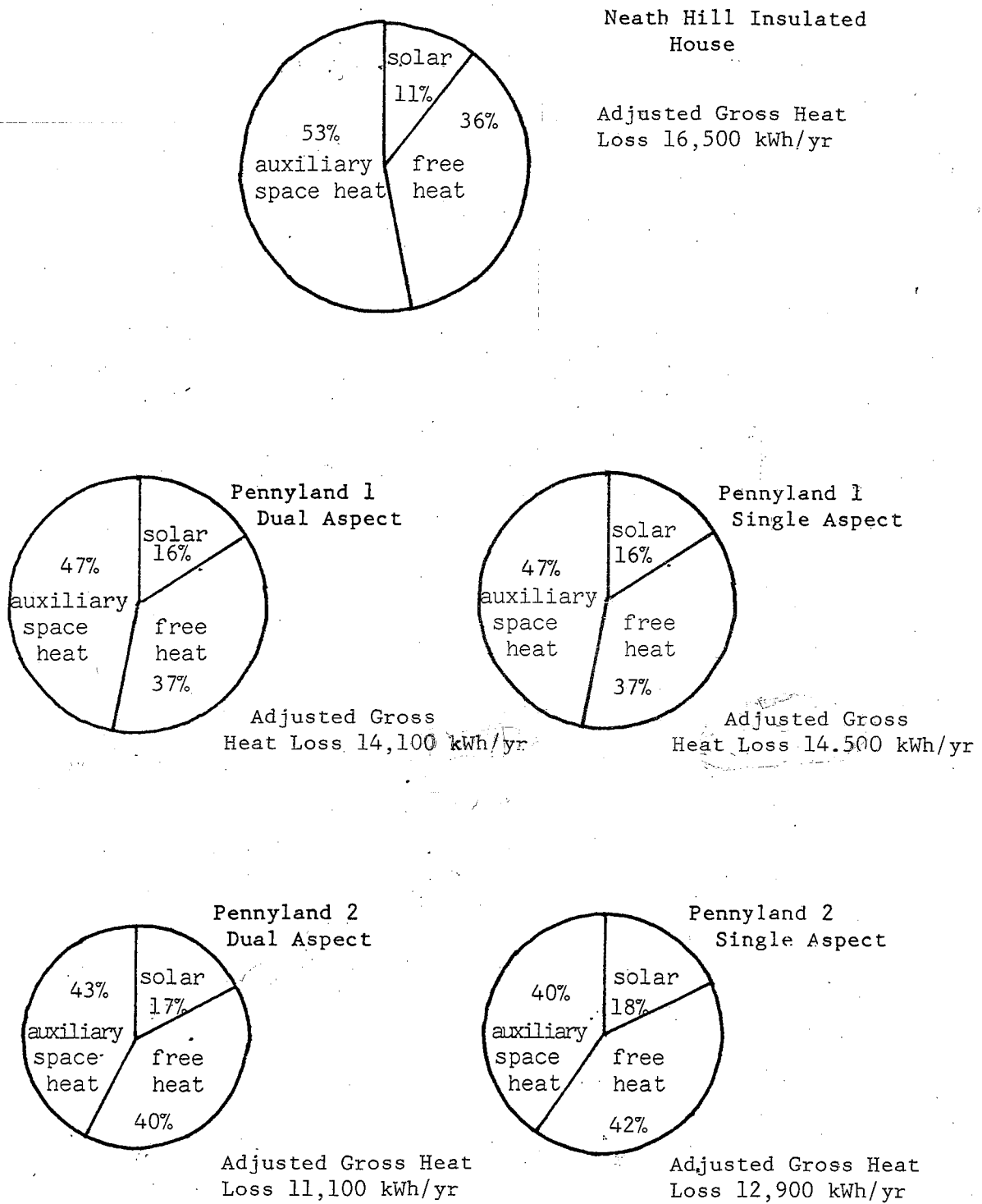
The actual proportion of solar gains does not increase dramatically as the insulation level is improved. This is because the length of the heating season reduces with improved insulation and more of the solar gains at the ends of the heating season are deemed unnecessary. This is a consequence of taking free heat gains into account first.

Also, there is little difference in the proportion of solar gains in the single and dual aspect houses, although figure 5.21 clearly shows a larger absolute solar gain in the single aspect type. This is due to the larger heat losses of the single aspect houses. The extra solar gains simply go to make up the extra energy consumption.

The more detailed studies in the Linford project have shown that both absolute and marginal solar gains are highly dependent on the manner of use of the house, in particular the length of the heating season. There is little solar radiation available in the deep winter months and matters critically depend on how far into the sunnier spring and autumn the heating season actually extends. Readers are referred to the Linford project report for a discussion of this topic.

Finally, the house energy balance can be presented as a Sankey diagram. Such a plot for the Neath Hill Insulated house type and one for a Pennyland Area 2 single aspect house are shown in figure 5.23. This graphically shows the energy inputs and losses for the two house types. Perhaps the most important features to note is how a 25% reduction in total house heat loss coefficient, together with the use of a more efficient gas boiler has produced a massive reduction in gas consumption. In particular, flue losses and useful space heating consumption have both been halved.

Figure 5.22

Annual Energy Contributions to Adjusted
Gross Heat Loss

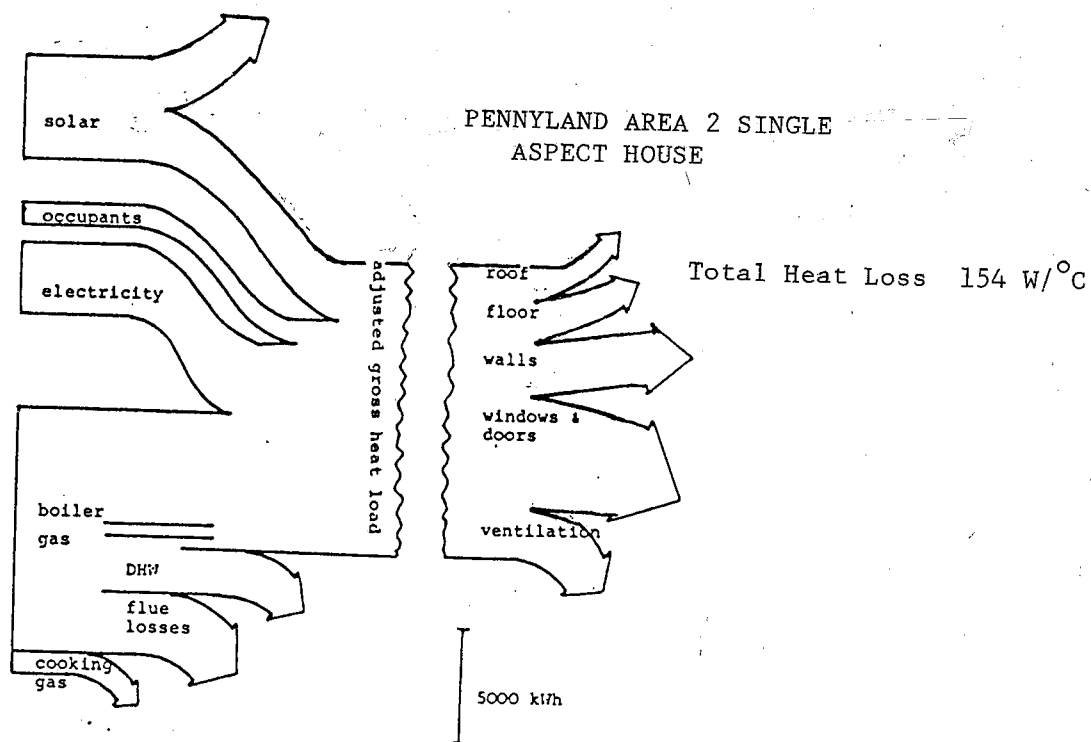
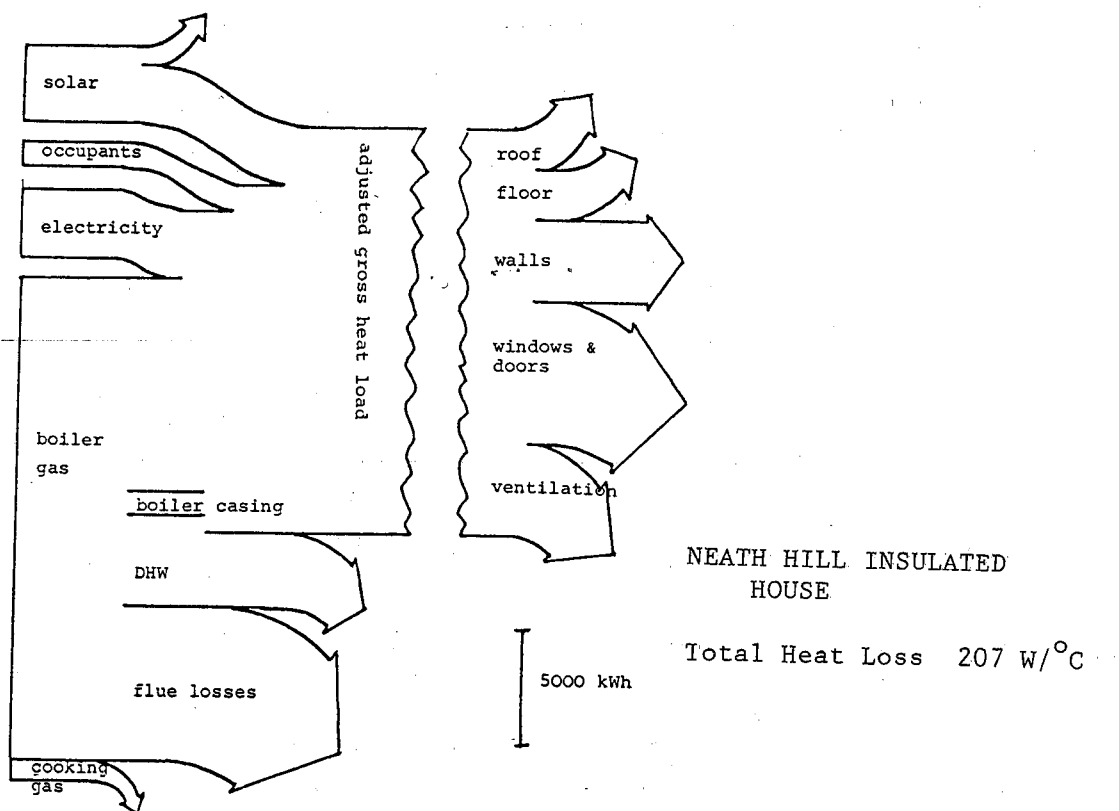


Figure 5.23 Sankey Diagrams (see Appendix 11 for others)

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CHAPTER 6

DETAILED ANALYSIS

CONTENTS

- 6.1 Overview of Methods of Analysis
- 6.2 Statistical Analysis of Annual Space Heating
- 6.3 House Characterisation
- 6.4 Energy Balances
- 6.5 Extending the Design Modelling
- 6.6 Comparison of Measurements and Modelling
- 6.7 Wider Comparisons

This chapter examines the data in more detail, refining the group energy comparisons, determining the solar gains and using computer modelling to produce best estimates of the project energy savings.

"I have yet to see any problem, however complicated, which when you looked at it the right way, did not become still more complicated".

Poul Anderson.

6. DETAILED ANALYSIS

6.1. Overview of the Methods of Analysis

The Pennyland project has generated a vast amount of data on the energy consumption in 170 houses. As explained in the previous sections the simple comparisons, planned when the project was designed, no longer make much sense. There is a much wider range of house types and sizes than initially conceived and the Neath Hill control has proved to be so different from the Pennyland estate in several important respects that it cannot serve as a control against which to measure solar contributions. To make this clear it should be noted that the extra solar gains from the passive solar design are expected to be less than 1000 kWh/yr. The observed difference between Neath Hill and Pennyland is about 8000 kWh, of which 3000 kWh can be attributed to additional boiler losses, about 1500 kWh to differences in ventilation rates, perhaps another 1500 kWh due to differences in mean temperatures and about 2500 kWh to differences in water heating. All these estimates of differences are liable to considerable uncertainty, which, coupled with the inevitable variations between houses and the small sample sizes, means that there is no hope of identifying any residual difference of less than 1000 kWh by simply comparing annual or weekly fuel consumption figures.

Although the simple approach won't work it is possible to undertake more sophisticated analyses of the data available and attempt to obtain estimates of the solar contributions in other ways. All these additional methods of analysis introduce some additional knowledge, theory or data in order to reduce one or more sources of variation with the aim of leaving the differences we are seeking more apparent. We know that there are large differences in total energy consumption between the houses, as indicated in Figure 6.1. The question is "what are the factors causing these differences?" We know that there are random differences between the houses due to the different patterns of occupancy (different temperatures, ventilation rates, uses of appliances and hot water etc). We also expect there to be differences caused by differences in fabric loss due to both different levels of insulation and differences in levels of terracing (i.e. differences in external wall area etc). There will also be differences due to the different boilers used. And finally, we hope, differences due to the solar design.

In the previous chapter we have produced a fairly crude breakdown of the energy uses in the different house types, but we would like to know answers in more detail in order to make hard recommendations for future house design.

In the following sections we will present three different sorts of analysis and one synthesis, which all aim to improve the resolution of the project results, especially the solar ones.

A. Statistical Analysis

The first of these is a statistical analysis of annual total space heating consumptions, which aims to reduce the variation in the raw data by correcting for known differences between the houses. The three corrections applied are for differences in fabric loss due to levels of terracing, differences in mean internal temperatures, and differences in number of occupants. The correction factors themselves are derived from the data. Correction factors could have been worked out for the first two differences on a theoretical basis, but using the data itself seems more convincing.

The procedures succeed in improving the resolution of the results, but not sufficiently to produce any significant solar answers. An important discussion in this analysis involves the temperature correction of the data.

B. 'House Characterisation'

The second method, referred to as 'house characterisation', makes use of the fact that we have available weekly data on energy use. Since the temperature and solar radiation vary independantly from week to week the weekly data can be analysed to estimate the effect of each of these variables on the energy use. Making certain simplifying assumptions the energy balance of the house can be written as

$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

where	Q	is the auxiliary space heat
	K	is the sum of the incidental gains
	$\sum U.A$	is the house fabric specific loss
	C_v	is the ventilation specific loss
	ΔT	is the temperature difference (internal - external)
	R	is the effective solar aperture
	S	is the solar flux

This heat balance equation can be evaluated using statistical methods. Correlating Q against ΔT and S can produce estimates for K, $\sum U.A + C_v$, and R as unknowns. Alternatively, we can ignore the solar gains, concentrating on dull weeks only and using estimates for K from measured electricity use and cooking. By plotting Q+K against ΔT for dull weeks, we can estimate $\sum U.A + C_v$, as shown in figure 6.2.

Another procedure, used mainly in the Linford project, has been to plot $(Q+K)/\Delta T$ against $S/\Delta T$. As shown in figure 6.3 this plot gives estimates for both the total house heat loss $\sum U.A + C_v$ and the solar aperture or 'recuperation factor', R.

TOTAL ANNUAL GAS CONSUMPTIONS

October 1981 - September 1982

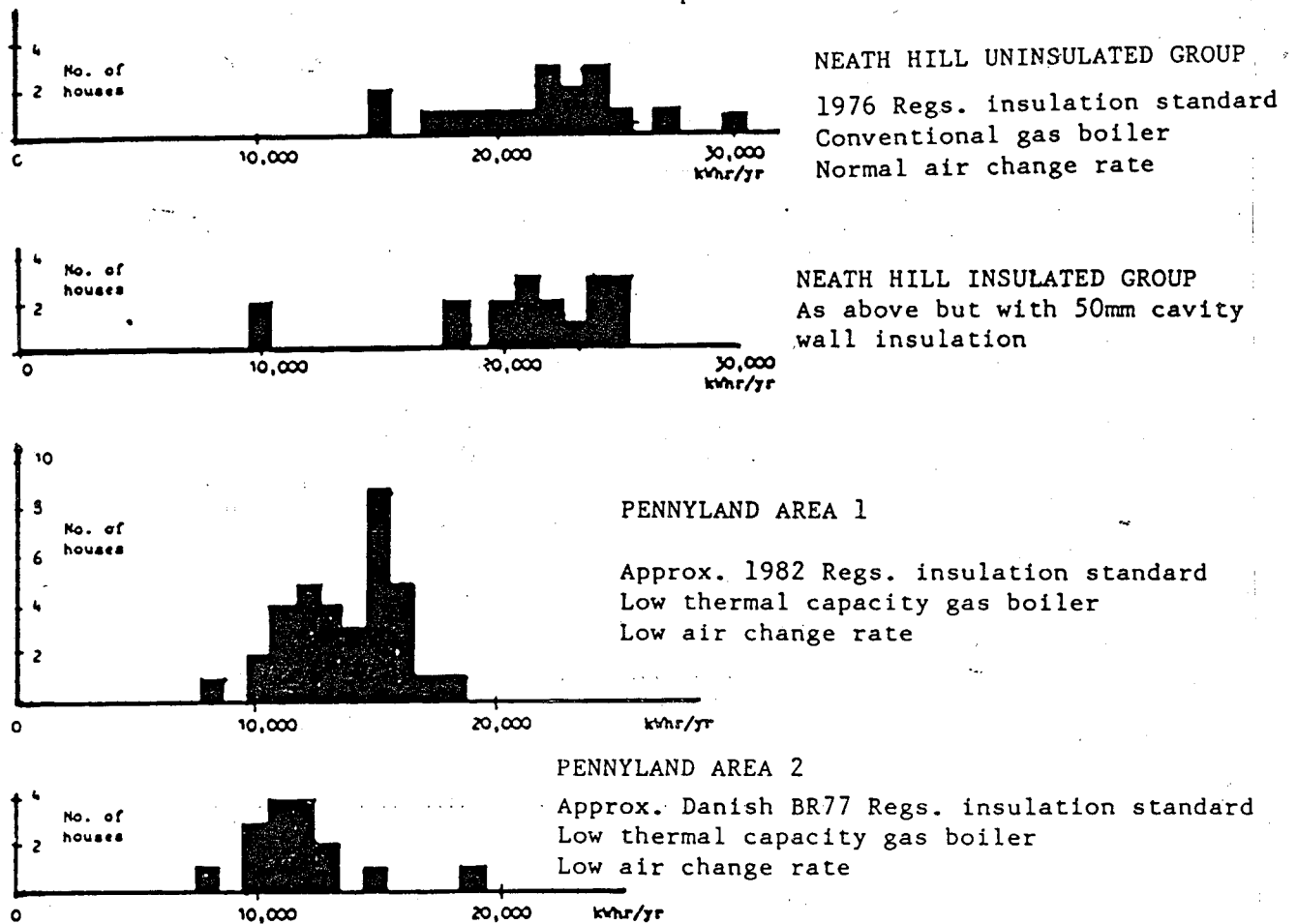


Figure 6.1 Annual gas consumptions for the four main insulation groups

'HOUSE CHARACTERISATION'

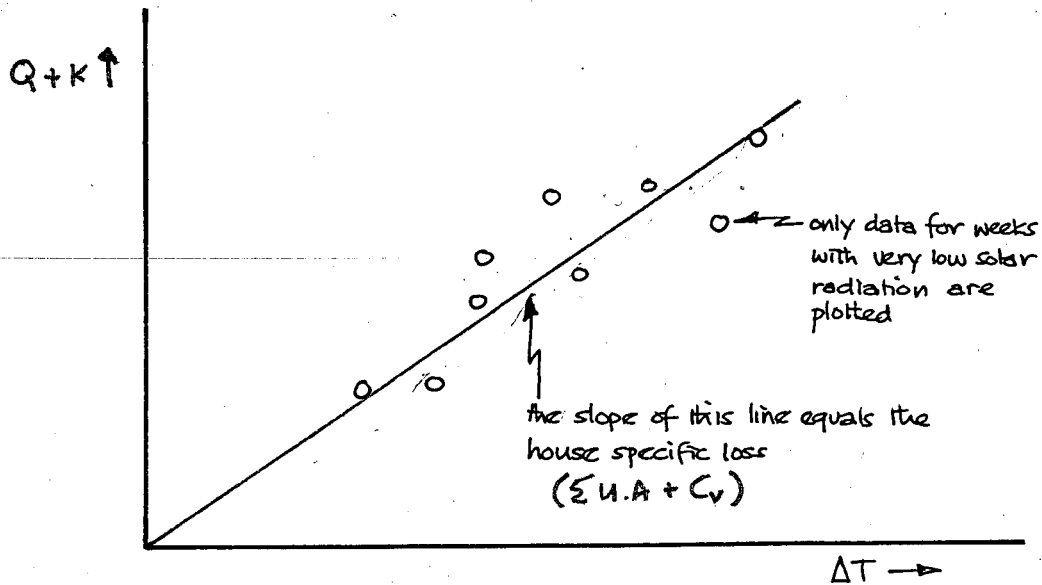


Figure 6.2 The plot of $(Q+K) \vee \Delta T$ can be used to estimate the house specific loss

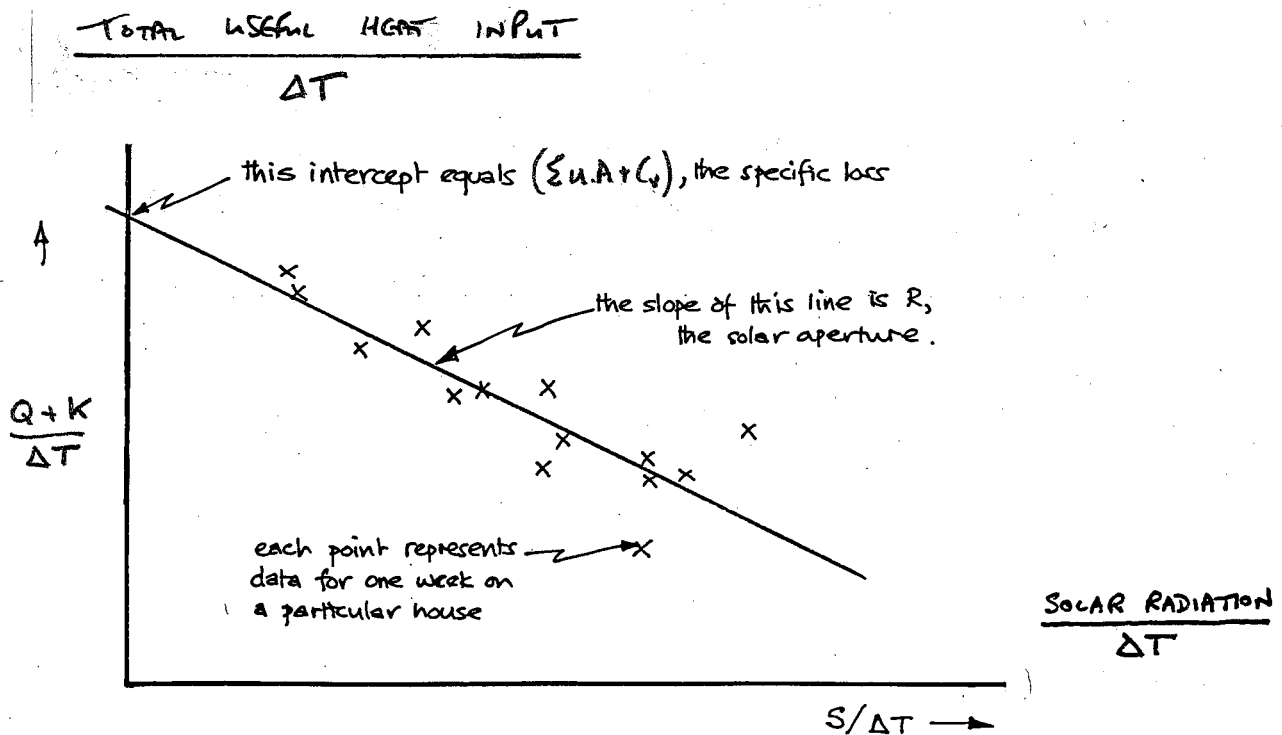


Figure 6.3 A plot of $(Q+K)/\Delta T \vee S/\Delta T$ provides estimates of both the solar aperture and the specific loss

C. Energy Balance Method

The third procedure used to analyse the data is the Energy Balance method. In this method a full energy balance for each house (or group of houses) is assembled from all the best data available. In order to compute this balance for each time period (the analysis is done weekly and combined into monthly and annual totals) extra assumptions have to be introduced about the terms which are not measured directly. The full balance is

$$\begin{array}{ccccccc} \text{incidental} & + & \text{solar} & + & \text{boiler} & = & \text{fabric} & + & \text{ventilation} & + & \text{DHW} & + & \text{flue} \\ \text{gains} & & \text{gains} & & \text{gas} & & \text{loss} & & \text{loss} & & \text{loss} & & \text{loss} \end{array}$$

The details of how the balances have been assembled are set out in Appendix 11. There have been two procedures used. The first estimates the solar gains from an assumed solar aperture and leaves the ventilation loss to be estimated as a residual in the balance. The second procedure estimates the ventilation loss from the pressure test data coupled to a simple model (described in Appendix 7). In this second balance the solar gains are left as the residual, and are thus estimated by a different route. The main problem with estimating either the ventilation loss or the solar gains by this method is that the errors in all the other terms are compounded into the estimate made.

This method is important, since it was the one suggested for use in a Europe-wide analysis of performance of passive solar houses as part of the C.E.C. Solar Energy Programme.

D. Extending the design modelling

The fourth method used was a 'synthesis' rather than an 'analysis'. By bringing together the experimental results of both the Linford and Pennyland projects and other new information, it has been possible to update the design computer model. This has then been used to estimate the energy consumptions of the various experimental house types and provide a detailed breakdown of the energy savings.

Although this method can produce very definite statements of savings not clouded by the statistical problems of the other methods, the credibility is very dependent on the mechanisms of the model itself and the degree to which it has been validated in various tests.

The detailed assumptions made in each method are discussed in the following sections. Although no individual method contains the 'whole answer', they all add up to provide a picture of the energy use in the houses and the magnitudes of the energy savings that have been made.

6.2. Statistical analysis of annual space heating

All the analyses presented in this section start with the best estimates of the useful space heating energy, derived by the processes explained in section 5.5. This means that use has already been made of the data collected and evaluated on the boiler efficiencies and gas used for water heating. For all the reasons set out in Section 5.5 this derived data is regarded as being the most accurate and useful data set on which to base the analyses.

First we shall discuss the statistical significance of these results, then we shall consider techniques for reducing the variation.

In order to illustrate the nature of the problem it is instructive to look at the best estimates that can be made of the savings from the data derived in section 5.5.

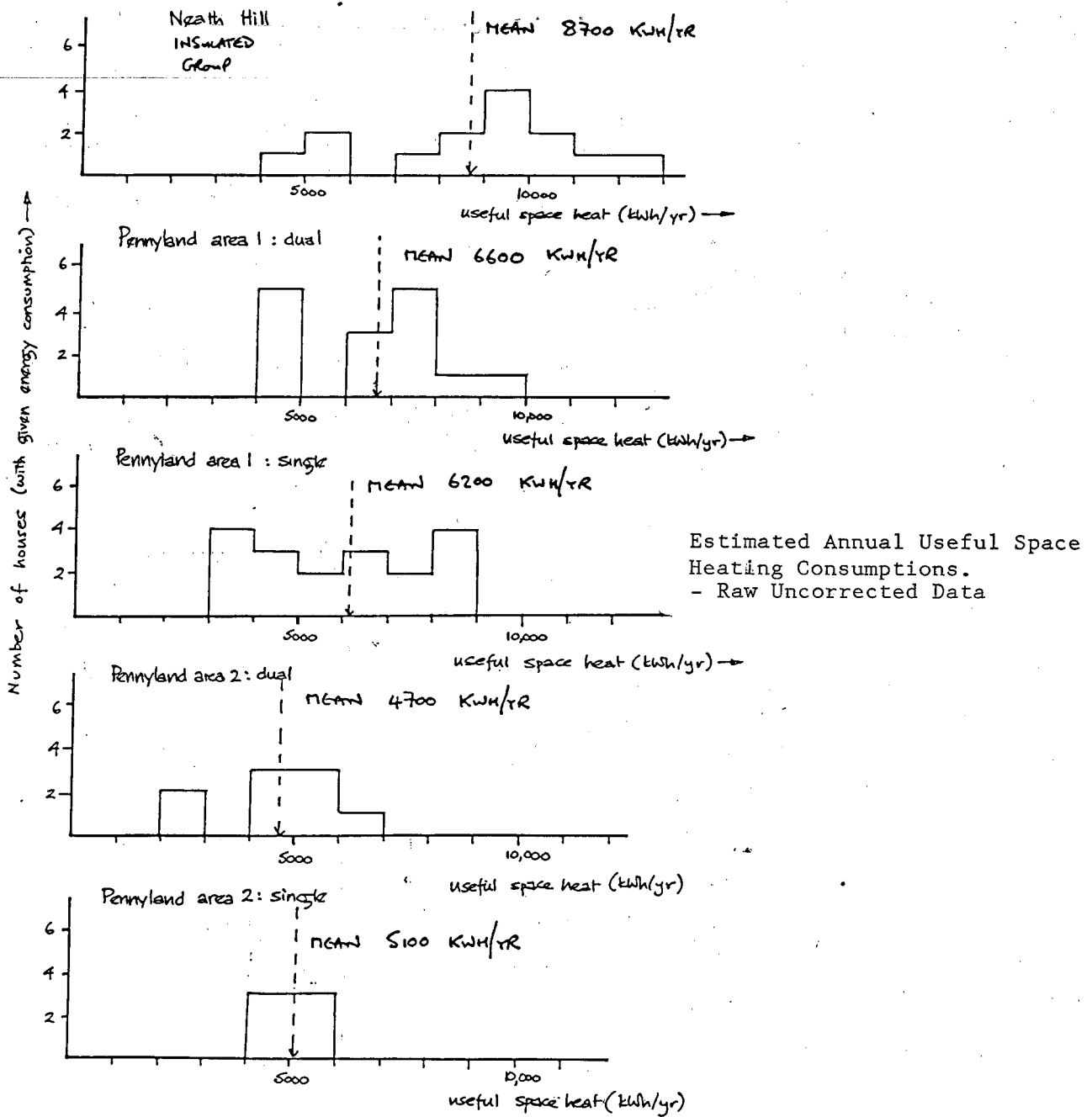
Histograms of the results of these computations for the 5-person houses for which there are good data sets are shown in Figure 6.4. The corresponding average values and savings are set out in Table 6.1. Also shown in the table are the "standard errors" associated with the data. These standard errors are based on the distribution of observed energy consumptions for each house type, they are NOT estimates of measurement errors. This standard error is the experimental equivalent of the standard deviation discussed in Section 2.3 and can be used, in conjunction with standard statistical tables, to estimate the confidence associated with an observation. As explained in section 2.3 (and Appendix 2) the confidence also depends upon the number of houses in the sample.

Table 6.1 Raw energy data and estimates of savings

House type	Useful space heat (kWh/yr)	Average energy savings		
		cf Neath H.	cf Penny. 1	Solar
Neath Hill	8700±590			
Pennyland 1	6400±420	2300±720		
Pennyland 2	4900±310	3800±700	1500±560	
Pennyland 1 dual aspect	6600±400			
single aspect	6200±450			450±600
Pennyland 2 dual aspect	4700±490			
single aspect	5100±200			-400±530

(Note: differences derived before rounding)

Figure 6.4



These results will be discussed in further detail below, but for now the point to note is that the insulation savings seem quite clear, that is the magnitude of the saving is several times the standard error. This is in fact a major result and appears to be the first time that a UK field trial has produced such clear evidence of energy savings from insulation.

There is one result which has not yet been presented, namely the comparison between the uninsulated and insulated groups on Neath Hill. This is not a happy comparison because the only data available on the uninsulated group is from quarterly gas bills, and as has been demonstrated these can obscure crucial detail. For the data to be compatible we compare the gross gas consumption of the two groups of houses. For the uninsulated group the gas consumption is 23400 kWh/yr, for the insulated group it is 20900 kWh/yr. The difference is 2500 kWh/yr with a standard error of 1700 kWh/yr.

This result is the product of an attempt to compare a selection of houses, like-with-like, and consequently does not agree with the figures shown in Chapter 1, which is for a larger sample of houses. The fact that the answer can change with the sample chosen simply illustrates the statistical problem.

The Statistical significance of the Raw results

The statistical t-test has been used to assess the statistical significance of the results. It is found that the difference between the Pennyland 1 and Pennyland 2 is significant at the 99% level; in other words such a difference would only occur by chance in 1 out of 100 cases.

This clearly indicates that there is some reduction in energy consumption associated with the increased insulation.

However the 95% confidence interval for this energy saving is roughly 300 to 2700 kWh/a. This is a very wide range - the fact that we are 99% certain that there is actually an energy saving does not mean that we know precisely what that saving is. This uncertainty is important, for example for economic analysis. Put simply, our 95% confidence interval would imply a 9 to 1 range of possible pay back times for the technical measures introduced at Pennyland 2. To be certain that these measures are worthwhile we need to try to narrow this range down.

An even clearer result is the energy saving of Pennyland 2 over Neath Hill. The probability that there is an energy saving here is better than 99.9%, and the 95% confidence interval for the saving is roughly 2300 to

5300 kWh/a. Bear in mind that this difference excludes differences due to the heating system - it is an estimate of the effect of the changes in the building fabric and estate layout only. Having said that this result is clearer than the insulation saving at Pennyland, it must be said that the question is less clear. There are so many differences between Pennyland and Neath that the contribution of any one of them to the overall saving is no more certain than the insulation saving at Pennyland.

Finally the marginal passive solar savings at Pennyland are very uncertain. The 95% confidence intervals at Pennyland 1 and 2 are about -1000 to +2000 kWh/a and -2000 to +1000 kWh/a respectively. This is too wide a range to be particularly useful.

Within-group corrections

It is known that the useful space heating of a house will depend upon the fabric loss and the mean internal temperature over the heating season. There will also be some dependence on the number of people in the house since this will affect the sum of the incidental gains. It is also known that these factors vary widely from one house to another. The first step in reducing the variation in the energy consumptions is therefore to develop a procedure for correcting for these differences within any one group of houses. The range of fabric losses and heating season mean temperatures are illustrated, for Pennyland 1 dual aspect houses, in Figure 6.5.

The procedure which was used to make this correction was to use the data itself to estimate the coefficients which relate energy consumption to these variables. Different combinations of variables were tried and it was found that the variance was reduced most by using the product of fabric loss and temperature difference plus occupancy. The coefficients were estimated by a least squares fit to an equation of the form

$$Q = a (F \Delta T) + b P + c$$

where

a, b and c are coefficients

Q is the useful space heat

F is the fabric loss

ΔT is the heating season average temperature difference

P is the number of people

* It seems that in our area of endeavour one can either have clear answers to rather woolly questions, or woolly answers to clear questions, but rarely clear answers to clear questions.

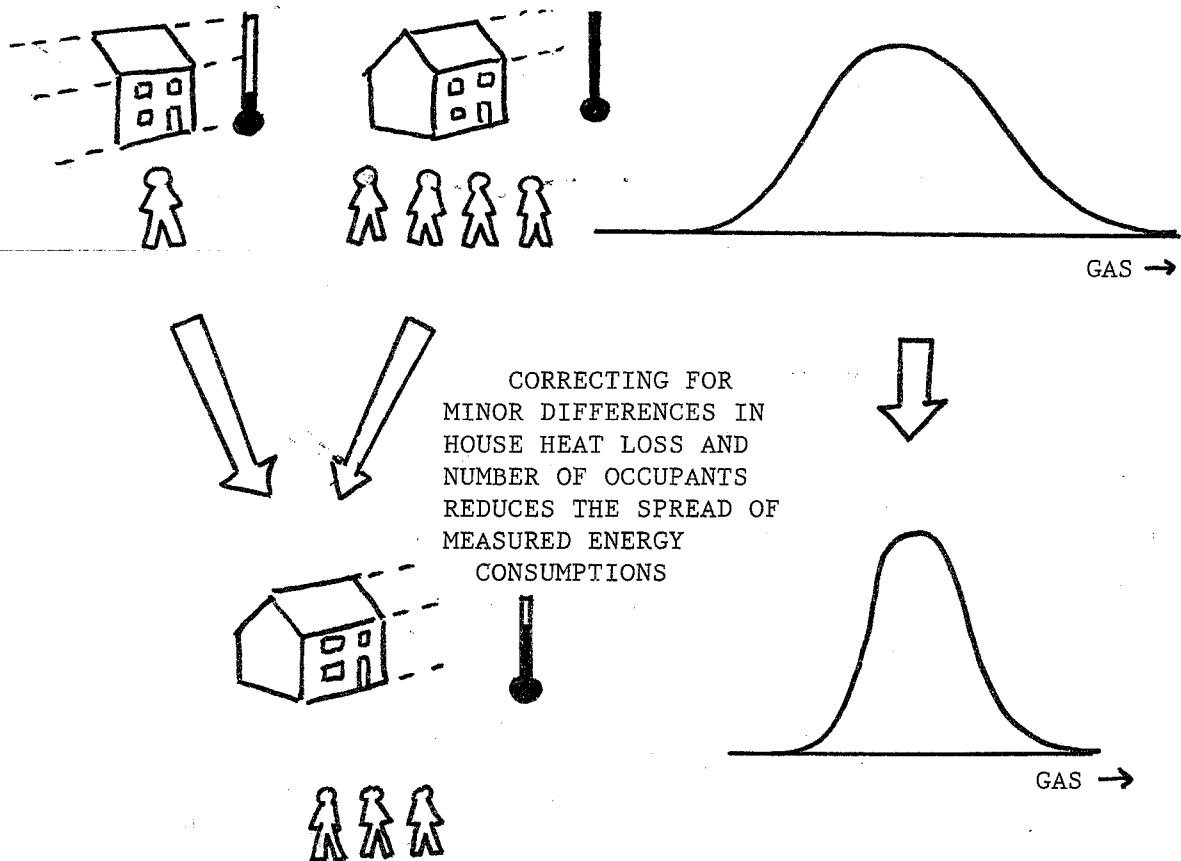
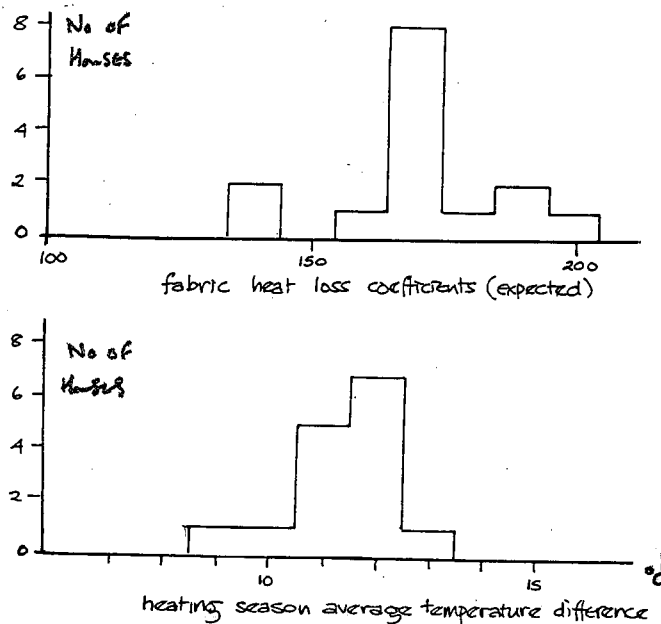


FIGURE 6.5

VARIATION OF HOUSE
FABRIC HEAT LOSS
AND INTERNAL
TEMPERATURE IN
PENNYLAND AREA 1



Initially individual house groups were tried in the regression equation, but the coefficients produced were not particularly statistically significant. The effect of the number of occupants, in particular, was very weak. It seemed to be positive (i.e. increasing space heating use with number of occupants) except in one group, the Pennyland 1 dual aspect houses, where it was negative (i.e. more occupants use less space heating energy).

Similar results were noted in relating water heating consumption with number of occupants and it is possible that the space heating effect is either due to genuine interactions between hot water consumption and space heating demand by way of free heat gains, or due to imperfections in the process of separating water heating from total gas consumption as described in section 5.6.

For the purposes of correcting the distributions in this chapter a pooled estimate of the $F\Delta T$ coefficient has been used from all the groups, but separate occupant coefficients were used for the Pennyland 1 dual aspect house groups and all the others, viz:-

Weighted $F\Delta T$ coefficient	=	0.39 ± 0.05
Occupancy coeff. for PlDA	=	-89 ± 13 W/person = -800 ± 120 kWh/yr/person
Occupancy coeff. for rest	=	57 ± 22 W/person = $+600 \pm 200$ kWh/yr/person

There is little that we can say about the likely values for these coefficients. We would expect a value of about 0.5-0.6 for the $F\Delta T$ coefficient. This is simply the fraction of the year occupied by the heating season (i.e. Oct-Apr.). The value of 0.39 is reasonable given the tendency of least squares regression procedures to underestimate coefficients given a less than perfect fit.

It is easy to think of reasons why the occupancy coefficient should be either positive or negative. Why it should be both is simply a mystery. Fortunately, the occupancy correction has not been very important in the group comparisons.

Using these coefficients the energy consumption for each house could be corrected to the average internal temperature for the group and to the fabric loss associated with an end of terrace house in that group. All the consumptions were also adjusted to three occupants per house.

The resulting histograms are shown in Figure 6.6. As hoped the variance has significantly reduced. It is now also noticeable that the distributions of energy use appear more gaussian (i.e. closer to a bell shaped ideal distribution). The corrected estimates of the useful space heating, and the corresponding savings, are set out in Table 6.2.

Table 6.2 Corrected energy data and estimates of savings

House type	Useful space heat (kWh/yr)	Average energy savings		
		cf Neath H.	cf Penny. 1	dual-single
Neath Hill	8800 \pm 360			
Pennyland 1	6500 \pm 330	2300 \pm 490		
Pennyland 2	5100 \pm 310	3700 \pm 420	1400 \pm 400	
Pennyland 1 dual aspect single aspect	6500 \pm 330 6600 \pm 320			-130 \pm 460
Pennyland 2 dual aspect single aspect	5100 \pm 310 5200 \pm 80			-50 \pm 310

(Note: differences derived before rounding)

As might be expected, the biggest effect of making these corrections is on the uncertainty in the energy savings. The energy consumptions and savings themselves do not move very much. We are now more than 99.9% certain that the application of the Pennyland 2 insulation measures would result in an energy saving compared to houses built to the Pennyland 1 level. Perhaps more importantly, the 95% confidence interval of this saving is now roughly 540 to 2300 kWh/a. Although this is still a 5 to 1 range, it is an improvement on 9 to 1 for the raw estimates, and moreover the lower limit has risen by nearly a factor of 2. Less stringently, we are 90% certain that this saving is bigger than about 860 kWh/a.

The 95% confidence interval for the saving due to the application of the Pennyland 1 measures compared with Neath Hill is about 1200 to 3400 kWh/yr.

Raw space heating
estimates from figure 6.4

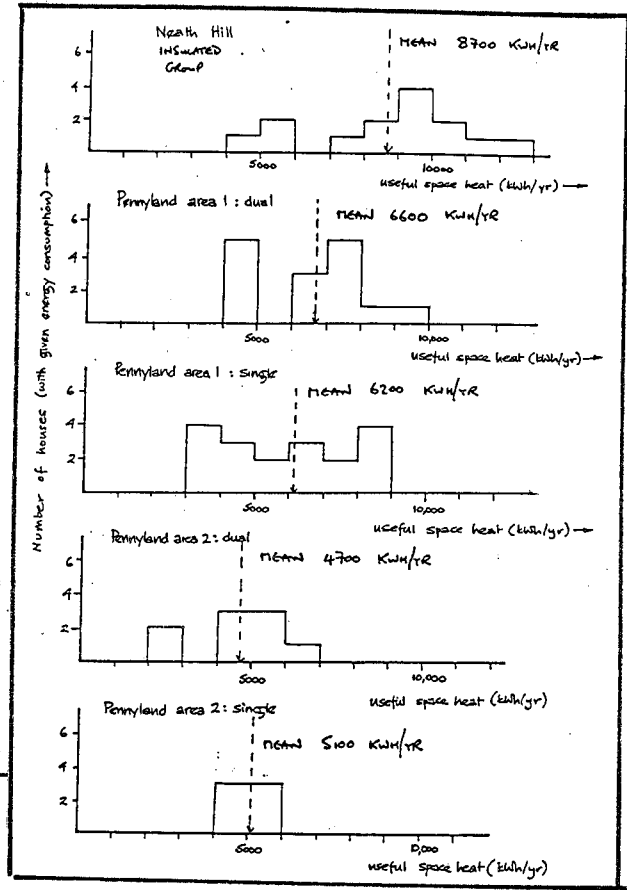
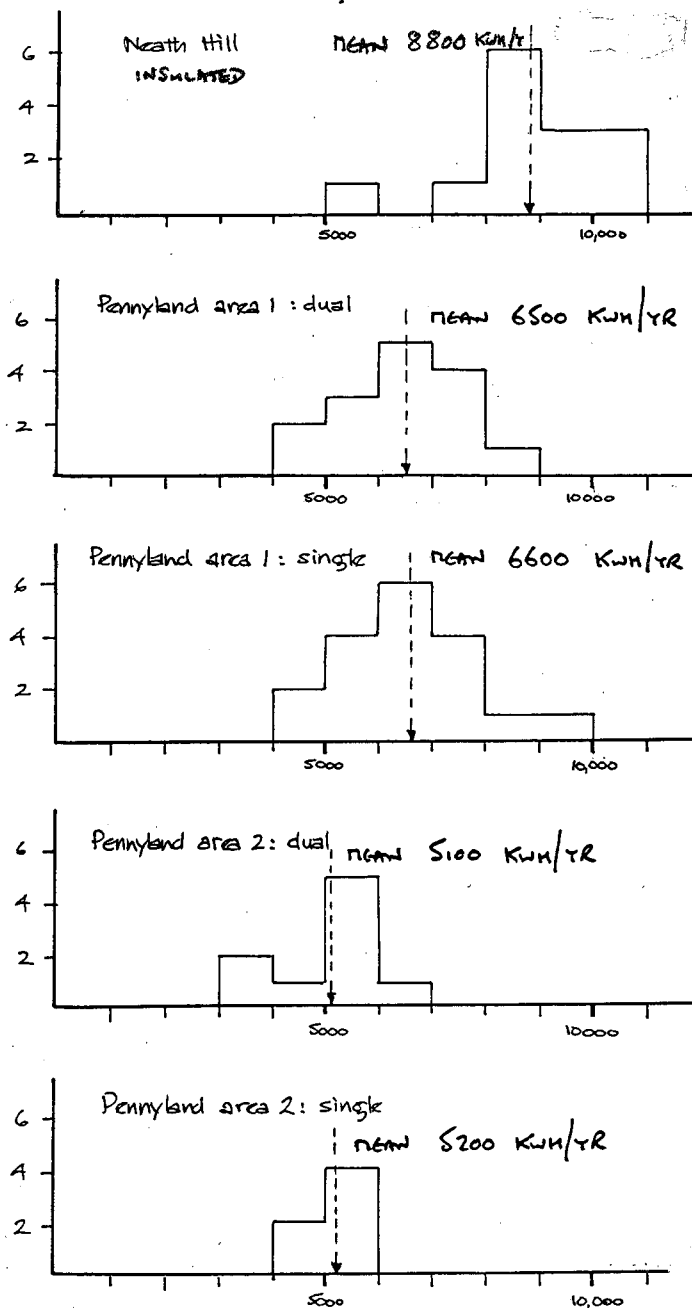


Figure 6.6

Correcting for
within-group
variations in
fabric loss and
internal temperature
reduces variance
by about 30%.

Again the solar savings, are not significant. The 95% confidence intervals are about ± 1000 in both area 1 and area 2 houses. This is what we expected, though obviously narrower confidence intervals would be desirable.

Between-group corrections

Although the above procedure has reduced the variation within each group there remain a number of significant differences between the groups of houses that have not yet been corrected. By using the calculated estimates of useful space heating the differences in boilers between Neath Hill and Pennyland has already been taken into account. However an examination of the average values of the fabric losses, internal temperatures and occupancy shows that there remain important differences in the last two variables (obviously differences in the fabric loss are not to be eliminated - they are differences we wish to examine!) The values are set out in Table 6.3

Table 6.3 Average values of fabric loss, heating season temperature differences and number of occupants.

House type	Sample size	Fabric losses end terrace	average terrace	Temperature difference (htg season)	Occupants (number)
Neath Hill	14	171	165	13.5	3.3
Pennyland 1 dual aspect	15	171	172	11.4	3.2
single aspect	18	193	180	12.8	3.2
Pennyland 2 dual aspect	9	115	108	12.4	2.8
single aspect	6	129	124	14.0	2.8

The dominant difference between the groups of houses is in the temperature. There is a 1°C difference between insulation levels and 1.5°C difference between dual and single aspect houses. Obviously these temperature differences will affect the energy consumption, as discussed in section 5.6.1 and illustrated in Figure 6.7. In Figure 6.7 the top curve represents the variation in energy with temperature for a Pennyland area 1 type house, the bottom curve shows the same for a Pennyland area 2 type house. The average temperature on Pennyland area 1 is shown as P1, P2 shows the average temperature for Pennyland area 2 houses. The

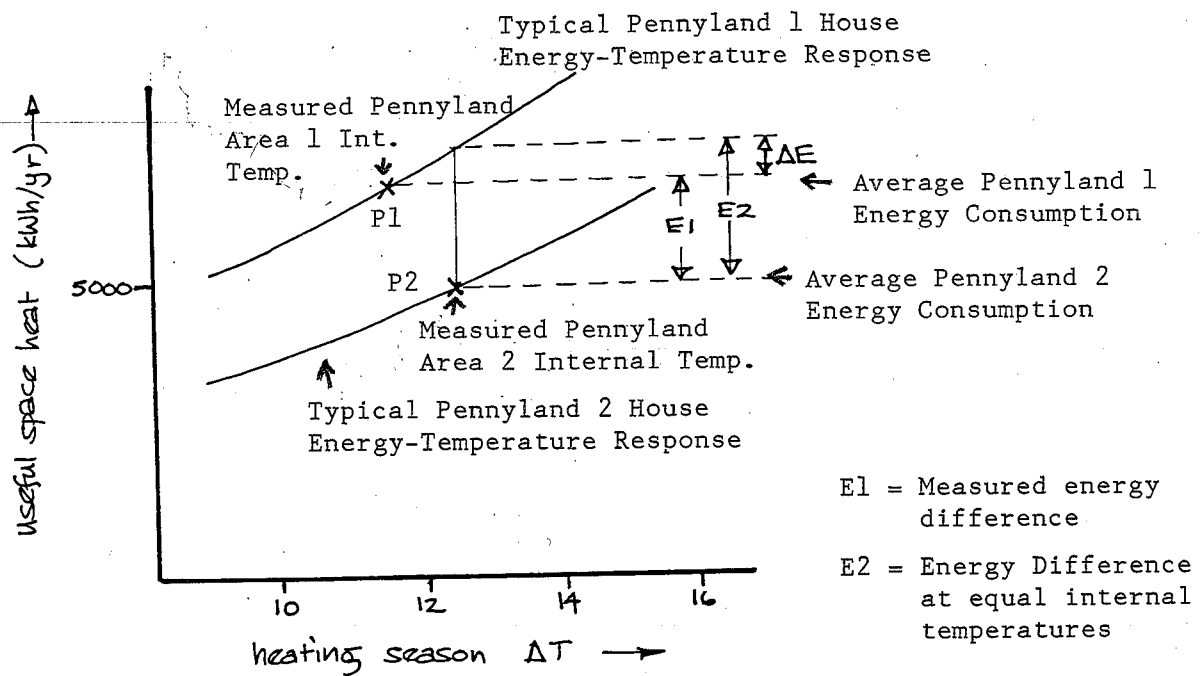


Figure 6.7 Illustrating the relationship between average heating season temperature differences and useful space heat savings

observed difference in space heating energy is E_1 . The energy that would have been saved had both groups of houses had the same temperature is shown as E_2 . In this example the difference between these two estimates of the saving is 600 kWh/yr.

The difficulty that we face is that we are not simply trying to account for physical energy flows and temperatures, but to guess how valuable these are to people. We have no way of knowing whether the occupants of Pennyland 2 and the single aspect houses value these temperature bonuses (which occur mainly in the bedrooms) as much as the energy savings which have been forgone to obtain them. If the temperature bonus is as valuable to people as the lost energy saving $\Delta E'$ then it is useful to estimate the energy saving that would have occurred if both groups had had the same mean temperatures. (Perhaps this should be called the isothermal energy saving?) If the value of the temperature bonus is zero then the most useful indicator of the energy saving is the raw energy saving. The area is complex (see for example ref. 6.1). We will estimate both the energy savings with and without the energy saving value of the temperature differences between the groups of houses, and leave the reader to decide which is the most appropriate to use for themselves.

The discussion of the effects of temperature differences between the groups has been quite long. This was necessary because temperature is not independent of insulation level or solar design. The two other between-group variations that we mentioned earlier (number of occupants and terracing level) are independent of insulation and solar design, and we therefore feel justified in attempting to correct the auxiliary energy consumptions for these differences.

Figure 6.8 shows the effect of correcting the space heating energy used to a common heating season average internal temperature 18°C . The corrections were carried out using the same coefficients as for the within group corrections. The main effect is to increase the difference between the Pennyland insulation levels, to reduce the difference between Pennyland and Neath Hill and to increase the energy savings of the single aspect houses at Pennyland compared with the dual aspect houses. The first of these is what would be expected - insulating houses

There may be some subtle connections between the layout of an estate of single aspect houses compared with one of dual aspect houses which could introduce a connection between passive solar variant and terracing, but this is beyond the scope of this report. The observed correlation between insulation level and number of occupants at Pennyland and Neath Hill is probably due to the fact that the better insulated houses were occupied later, and their occupants have therefore had less time to raise families.

Within-group corrected data
from figure 6.6

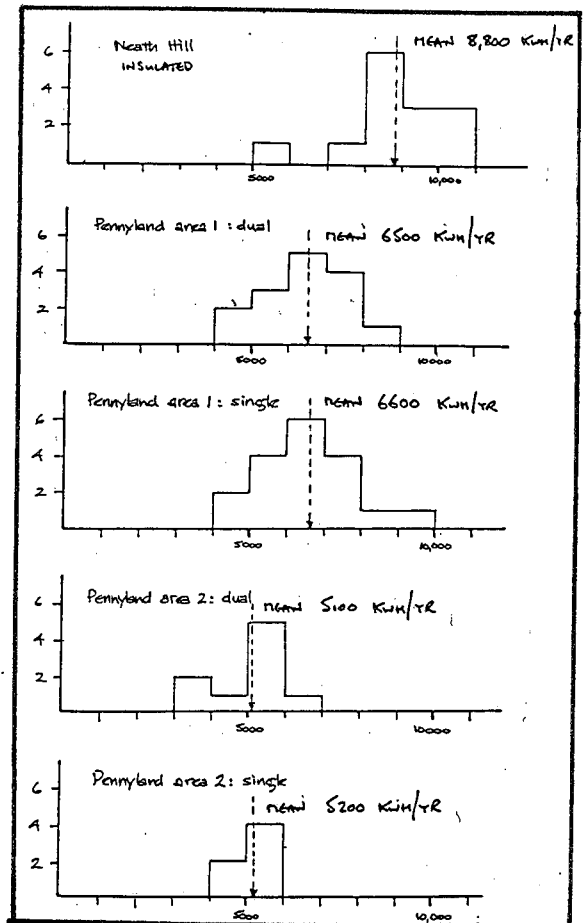
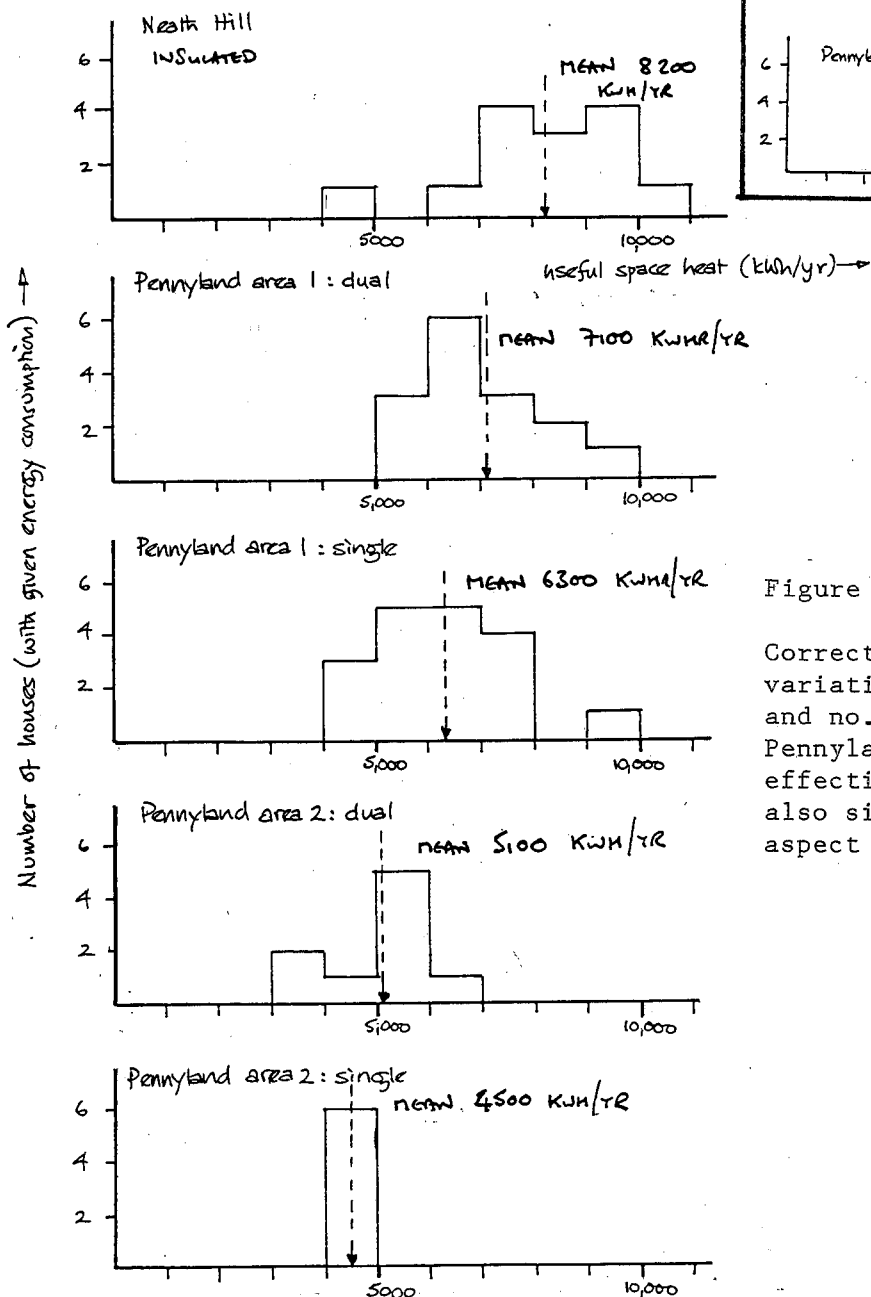


Figure 6.8

Correcting for between-group variations in internal temp. and no. of occupants increases Pennyland 1 - Pennyland 2 effective energy savings and also single aspect - dual aspect difference.

tends to result in higher temperatures, particularly in houses which do not have full central heating systems, and where the heating system is used intermittently. Correcting for such temperature rises increases apparent savings. The second is not really what we would expect, but we know of several possible reasons for the difference in temperatures between Pennyland 1 and Neath Hill - higher infiltration rates at Neath Hill, differences in room layout, and not least the fact that some of the Neath Hill houses have full central heating systems. The effects of the solarisation of the Pennyland single aspect houses is qualitatively what would be expected, but for two reasons the temperature differences between the dual and single aspect houses may be exaggerated - the first is the problem of the siting of the external temperature probes in the dual aspect houses on Pennyland 1, and the second is the fact that the temperature probes upstairs are in south facing bedrooms. The new average energy consumptions and savings are as set out in Table 6.4

Table 6.4 Corrected energy data and estimates of savings
(corrected to same average internal temperature)

House type	Useful space heat (kWh/yr)	Average energy savings		
		cf Neath H.	cf Penny. 1	dual-single
Neath Hill Insulated	8200±360			
Pennyland 1	6700±330	1500±490		
Pennyland 2	4800±270	3400±420	1900±400	
Pennyland 1 dual aspect	7100±330			
single aspect	6300±320			750 ±460
Pennyland 2 dual aspect	5100±310			
single aspect	4500±80			630 ±310

(Note: differences derived before rounding)

The 95% confidence interval for the Pennyland 2 insulation measures compared with the Pennyland 1 level of insulation is now about 1000 to 2800 kWh/a. The width of the interval is the same as before when we were not counting the temperature difference between Pennyland 1 and 2 as an additional energy saving, but the ratio of the upper to the lower confidence limit is now only (!) 2.8 to 1.

On the basis of these figures, we are more than 99.9% sure that the results of this insulation step are equivalent to an energy saving, and we are 90% certain that the value of the saving is greater than about 1300 kWh/a.

The 95% confidence interval for the saving due to the application of the Pennyland 1 measures compared with Neath Hill is about 400 to 2600 kWh/a. On this basis the widespread application of Pennyland 1 construction techniques (assuming we have accurately identified the ones that make the difference!) has a 99% probability of giving an energy saving compared with Neath Hill type houses.

Counting temperature rises as equivalent to energy savings leads to quite a dramatic shift in the confidence intervals for the solar savings. There is now about a 90% probability that widespread application of the Pennyland single aspect as opposed to the dual aspect passive design would save energy or produce equivalent temperature increases. This result has to be quite heavily qualified however. The fact that the upstairs temperature was only sampled in south facing bedrooms will overestimate any effects of increasing the south facing window area of the house. Also the fact that outside temperature was measured on the north side of most of the Pennyland 1 dual aspect houses will tend to lead to overestimates of the effect of passive design on temperatures in these houses.

Conclusions from Statistical Analysis

A number of important conclusions can be drawn from the above analyses. These are summarised, in terms of the useful energy savings (except where stated), as follows.

Although the Neath Hill estate has failed to act as a control for the passive solar part of the experiment, the comparison between Pennyland and Neath Hill has demonstrated a number of significant energy savings.

1. There is a saving of about 3400 kWh/yr of gas due to the different boiler used on Pennyland. Whilst it is difficult to estimate the uncertainty in this figure it is certainly no more than ± 500 kWh/yr. This result is important since it is the largest single energy saving demonstrated in this project.
2. There is an additional difference of about 2000 kWh/yr in the useful space heating between Neath Hill and Pennyland 1. This can be attributed to some combination of differences in infiltration rates and solar gains. The raw difference is 2300 kWh/yr which remains the

same after correction for within-group differences in temperature and fabric heat loss. Adjusting the figure to a common temperature reduces the difference to 1500 kWh/yr. This is the same as the estimate made of the difference in ventilation loss (see section 4.6), though the large assumptions made do give this wide error margins. Given the large differences in boiler efficiency as well, it is impossible to say whether there is a solar difference (of the order of 500 kWh/yr) or not.

3. There is a highly statistically significant saving between areas 1 and 2 of the Pennyland estate. Perhaps the most cautious estimate is 1400 ± 400 kWh/yr. This would imply a minimum saving at 90% confidence of 860 kWh/yr. This estimate takes into account differences in terracing and within group temperature differences, but not the overall temperature difference between the two halves of the estate.

Allowing for this apparent internal temperature increase in Area 2 as an equivalent energy saving increases the saving estimate to 1900 ± 400 kWh/yr of useful space heating energy. This implies a minimum saving at 90% confidence of 1300 kWh/yr.

4. On the basis of both raw data and data corrected for within-group temperature variations, there is not any detectable difference in energy consumption between the single and dual aspect house designs.

There is, however, an apparent increase in internal temperature in the single aspect design, though some of this may be a monitoring artifact. If the increase in temperature between the two house types is taken as real and useful, there is a detected energy saving of approximately 700 ± 400 kWh/yr. This is significant at a 90% level.

6.3 House Characterisation

As outlined earlier, the weekly measured data can be analysed by statistical means to build up an energy balance of the form:-

$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

where

- Q = Weekly measured space heating
- K = Weekly free heat gains from cooking, lights, etc.
- $\sum U.A$ = House fabric heat loss
- C_v = House ventilation heat loss, assumed constant
- ΔT = Weekly average inside-outside temperature difference
- R = Equivalent clear 'solar aperture'
- S = Weekly total solar radiation on south-facing vertical surface

This statistical analysis can be done in several different ways:-

1. The 'triaxial' or 3-dimensional method. treating K, $\sum U.A + C_v$ & R as unknowns.
2. The 'low solar' method using only dull weeks when the solar gains can be ignored and assuming K to be known, to determine $\sum U.A + C_v$.
3. Siviour's two-dimensional method, assuming K to be known and determining $\sum U.A + C_v$ and R.

All of these methods have been used on the data with varying degrees of success. The last method has been used extensively on the Linford data to determine both the solar aperture and the house fabric heat loss under different conditions.

Linford test house results have shown that for really consistent answers it is necessary to measure both the floor heat loss and the continuously varying ventilation loss separately. The reason for measuring the floor loss independently is that solid floors of the type used at Pennyland and Linford respond more to a slowly changing soil temperature than external air temperature. The floor heat loss thus does not respond to the same ΔT as the walls or the roof.

Having produced good answers for the Linford test house, these showed good agreement with measurements in the adjacent occupied houses, although a large number of assumptions have been necessary.

A full description of the methods will be found in the Linford project report and also, with a discussion of the Pennyland results, in the companion Thermal Calibration report.

6.3.1 Solar Aperture

First a little explanation is required about the way in which the solar gains into a house have been treated.

It is assumed in the Pennyland and Linford projects that useful solar gains into a house are proportional on a daily or weekly basis to the measured solar radiation on the south-facing vertical surface, recorded outside the house and at 10 metres height (thus making it free from overshadowing problems). These measurements make no effort to exclude ground reflected radiation.

While this is not a perfect choice of solar variable, it is a good compromise between one that is a linear function of solar gains into a south-facing Pennyland/Linford type house and a 'meteorological' weather variable. South-facing solar radiation (excluding ground-reflected radiation) is measured at Bracknell and Lerwick and this data can thus be used to extrapolate results to other U.K. sites and years.

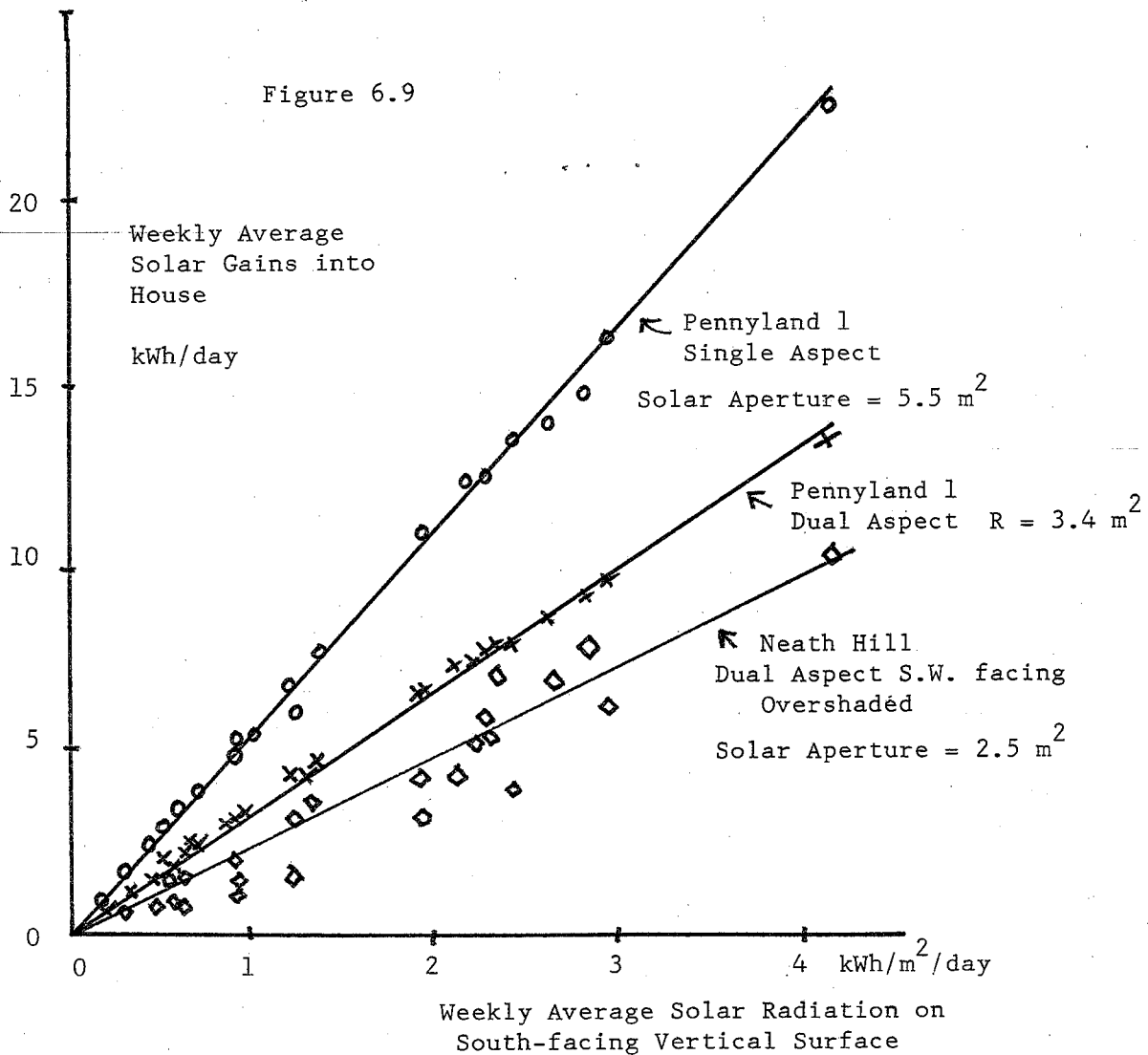
Previous projects and calculation systems have used solar radiation on the horizontal surface as the primary solar variable, with the result that solar gains into the house are a distinctly non-linear relation (see refs. 6.2 & 6.3).

The coefficient of proportionality of solar gains into the house to the south-facing vertical solar radiation is taken as being equivalent to a clear south-facing solar aperture. It must be stressed that this is purely a mathematical quantity, including as it does, gains on the north-facing side of the house and through the opaque brickwork, as well as the effects of overshading and window absorptivity. It is not directly related to the south-facing window area.

It has been given the symbol R since it is very similar in function to the solar 'recuperation coefficient' of the 'temperature without heating' calculation method developed at Liege (ref. 6.4).

Figure 6.9 shows computed solar gains into a Pennyland dual aspect house, a single aspect house, and a Neath Hill type dual aspect house, with overshading and facing south-west. This shows that the concept of a solar aperture with respect to south-facing solar radiation on the vertical surface is reasonable for the Pennyland houses but only roughly so for the Neath Hill ones.

It should be stressed that by 'useful' solar gains into a house we mean those that can be used either for increasing internal temperature or reducing space heating. Whether or not these solar gains are turned into a reduction in space heating requirement depends on many factors which cannot simply be determined (heating system control response, whether there is a space heating demand to be supplanted, etc.)



Solar gains into house as a function of south-facing vertical solar radiation.

Both quantities have been computed on an hourly basis, taking into account the transmission properties of windows and with an allowance for the reduced absorption due to net curtains derived from Linford measurements.

6.3.2. Triaxial Regression

Taking the heat balance equation

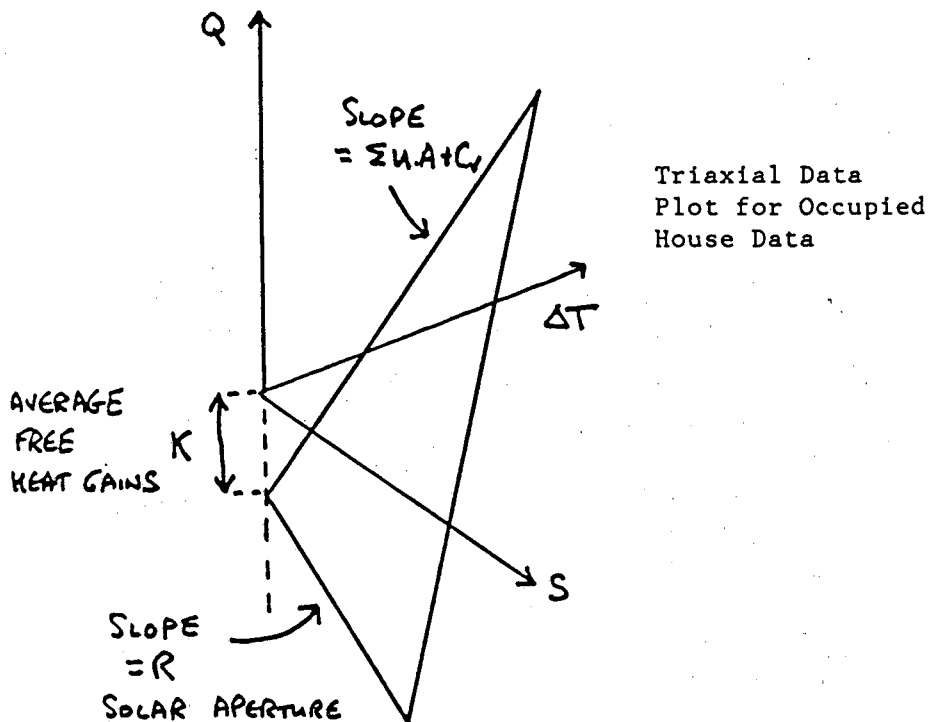
$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

and correlating Q with ΔT and S , it is possible to extract the three unknowns K , $\sum U.A + C_v$ and R .

This is equivalent to fitting a plane surface through data points lying in three-dimensional space between Q , ΔT and S axes.

Figure 6. 10

$$Q = (\sum U.A + C_v) \cdot \Delta T - K - R.S$$

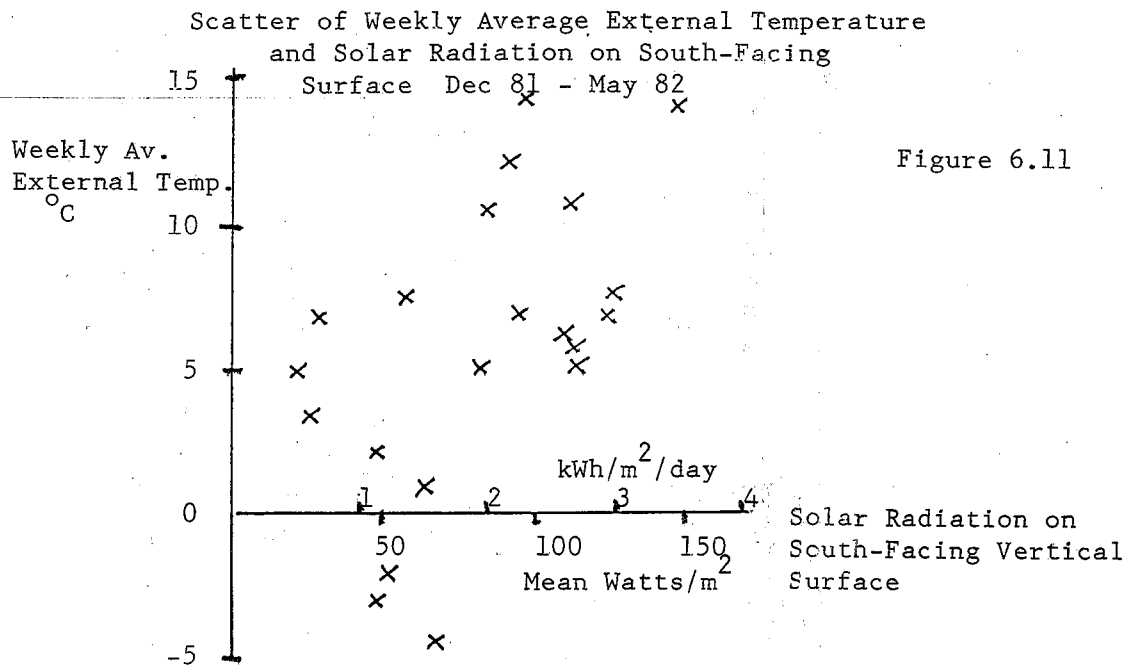


The slope of the intersection of this plane with that of the Q and ΔT axes should give the total house heat loss term $\sum A.U' + C_v$ and that with the Q and S axes should give the solar aperture R .

In practice, in assessing the performance of the house, we are at the mercy of available winter weather conditions to fix the various data points. As such, fitting a practical plane to them is not so easy.

In order to get a good fit to a plane we obviously need weeks with large values of ΔT and some with low values. We also need both sunny weeks and dull weeks. It is also vital that the two are not related, i.e. that the warm weeks are not all the sunny ones and that the dull

ones are not all cold. Fortunately the winter of 1981/82 has been obliging in producing a good mixture of weather. Figure 6.11 shows a scatterplot of weekly average outside air temperature and weekly average solar radiation from December 1981 to May 1982. This shows a good range of almost 20°C for the weekly average external air temperature and a reasonable range of weekly average solar radiation:-



The weather may not always be so suitable. An attempt to analyse the Linford test house data in this manner using ten weeks data from March to May 1982 was a miserable failure since the weather was just the same, week after week.

It is also vital to use 'clean' data for this kind of analysis, since least-squares regression is very sensitive to 'outliers' or odd points. For the two-dimensional methods these outliers can easily be seen when plotting the data, but when the data is in three dimensions, life is a little difficult. Various methods were tried to display the data, including 3-D computer graphics, ping-pong balls on string and plasticene on bits of wire, but all without much success. In practice outliers have been removed from the Pennyland data by using the 'large residual' detection procedure of the regression package itself. This is fine for the mathematics, but conveys little understanding of what is actually going on in the house.

The whole range of problems associated with this type of analysis are discussed in the companion Thermal Calibration report and research is still (June 1985) continuing on the topic.

Despite some doubts over the value of the method, it has managed to produce values of solar apertures for the various house designs that are in line with expected values, given the results from Linford.

Data has been pooled for each house type to give an 'average' house performance:-

Table 6.5 Estimates of solar apertures by weekly regressions

House group	aperture (sq.m)	sample size	theoretical value
Neath Hill	3.0±1.2	8	approx. 2.5
Pennyland 1	5.5±1.0	18	
Pennyland 2	4.1±0.7	7	
Pennyland 1			
dual aspect	3.7±0.9	9	
single aspect	7.3±1.7	9	
Pennyland 2			
dual aspect	5.0±0.8	3	
single aspect	3.4±0.9	4	
Pennyland 1&2			
dual aspect	4.0±0.7	12	3.4
single aspect	6.1±1.3	13	5.5

None of these answers is particularly statistically significant. The best estimate of the solar apertures for the single and dual aspect houses is given by pooling data from both Pennyland 1 and 2, giving effectively solar apertures of 4 m^2 for a dual aspect house and 6 m^2 for a single aspect one. These figures are comparable to values of 8 m^2 for the Linford test house with net curtains and 10 m^2 with no window clutter.

The values for the single and dual aspect houses also agree fairly well with those calculated by the computer model, in the light of the Linford results (see figure 6.9).

The regression values, including the 3 m^2 for the Neath Hill houses have been used to calculate solar gains in the 'fixed solar aperture' energy balances for the different house types.

These differences in solar aperture can be approximately be converted into differences in absolute solar contributions by multiplying by the total solar radiation incident over the heating season. This amounts to about $250 \text{ kWh/m}^2/\text{yr}$ on the south-facing vertical surface but is very dependent on the precise length of the heating season (see Linford report).

Thus the difference of about 1 m^2 in solar aperture between the Neath Hill houses and the Pennyland single aspect houses, corresponding to about 250 kWh/yr of heating energy, may be taken to be due to the correct orientation and avoidance of overshadowing, plus a slight rearrangement of glazing.

This figure is very similar to the value calculated by the NBSLD in section 6.5. Although it is at a very low level of statistical significance, this is the only measured indication from this project that the Pennyland dual aspect houses absorb more solar radiation than the Neath Hill control houses, other comparisons being clouded by the other differences between the house types (air infiltration, boiler efficiency, water use, etc.)

The 2 m^2 difference in solar aperture between the single and dual aspect designs, equivalent to about 500 kWh/yr, is also quite compatible with other measured results, bearing in mind the higher heat loss of the single aspect design and the low statistical certainty.

Since the solar apertures have been worked out using measured ΔT 's, these increased solar contributions will assume any increase in internal temperature over the heating season to be all useful. Also, the difference in solar aperture between the single and dual aspect houses may be in part an effect of the different placing of the external temperature probes, mentioned in the previous section.

6.3.3 Low Solar Method

The triaxial method can be simplified into two dimensions (thus producing printable graphs) by essentially ignoring the solar gains and using only dull weeks. Also, given that the researchers are probably better at estimating the free heat gain term, K , than the regression automaton, it has been assumed to be known. This has allowed estimates of $\sum U.A + C_v$ to be produced for all the intensively monitored houses, and using values of C_v estimated from the pressure tests, values of the fabric heat loss alone, which can be compared with the theoretical values.

The first procedure used was to select from the winter 1981/82 data set all the weeks for which the solar radiation was less than 60 W/m^2 average ($1.5 \text{ kWh/m}^2/\text{day}$). This effectively guarantees that the solar gains are less than about 15% of the total energy flow. The energy balance equation then reduces to:-

$$Q + K = (\sum U.A + C_v) \cdot \Delta T$$

If values of $Q+K$ are plotted against ΔT , then the slope of the resulting line gives an estimate of the total house heat loss $\sum U.A + C_v$. To a certain extent this assumes that C_v (and $\sum U.A$) is constant and independent of ΔT , which we know is not really true. These problems are discussed further in the Rapid Thermal Calibration report.

Figure 6.12 shows typical plots for three individual houses, a Neath Hill insulated type and one each from Pennyland Area 1 and 2. The fit to a straight line is fairly satisfying, though it is clear that without assuming that the lines go through the origin (i.e. that K is known), the slopes would be rather uncertain. The data does seem good enough to distinguish the 'energy signatures' of the Area 1 and Area 2 houses and at a lower confidence level, those of Neath Hill and Pennyland 1.

By pooling the data from many houses a composite 'energy signature' has been built up for all the houses in an area for which there were more than 5 data points and for which the regression line was a good fit. The results are shown in Table 6.6 below.

Estimates of total heat loss have been made both from heat meter space heating data and from gas meter data for a larger sample. The results are similar and about 10% lower than theoretical values taking into account ventilation rates estimated from pressure tests (see section 4.6).

Table 6.6 Estimates of total house heat loss from regressions

Estate	Based on heat meter		Based on gas meter		Theoretical value
	Total loss	Sample	Total loss	Sample	Total loss
Neath Hill Insulated	181 ± 35	5	190 ± 17	14	218
Pennyland 1	169 ± 10	11	163 ± 7	16	196
Pennyland 2	132 ± 7	8	124 ± 6	6	143

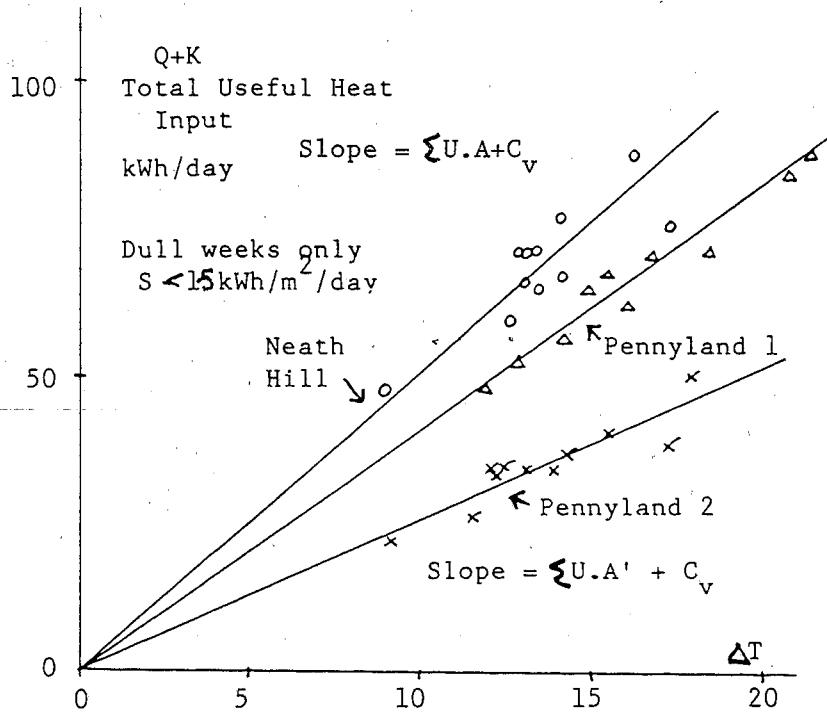
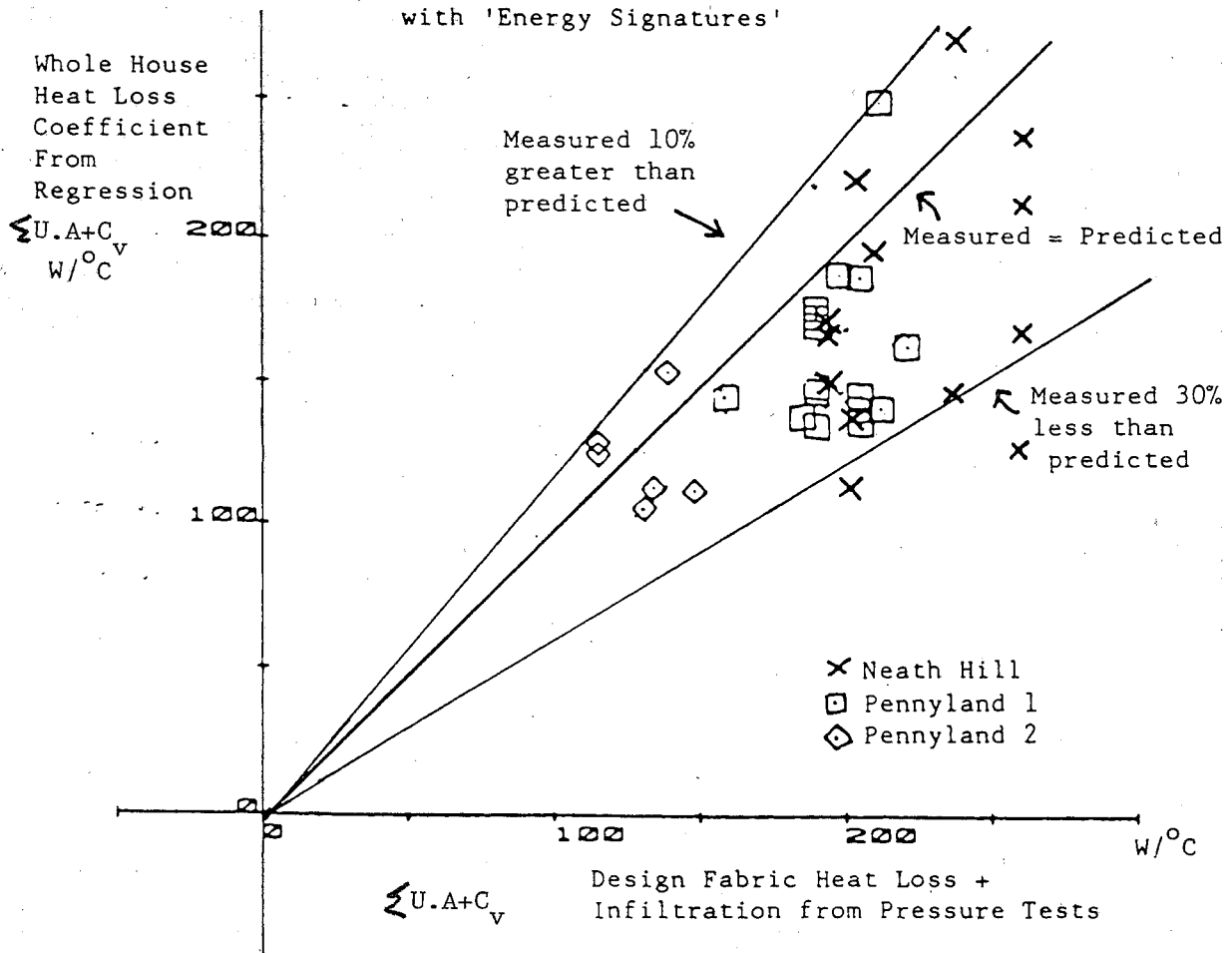


Figure 6.12 'Energy Signatures' of 3 different individual houses

Figure 6.13 Comparison of Design Heat Losses with 'Energy Signatures'



We can extend the process to individual houses. Figure 6.13 shows comparisons of values of total house heat loss calculated by regression with theoretical heat loss figures for individual houses from the three groups. Again there is a general tendency for the measured value to underestimate the predicted one by about 10%. The spread is from slightly under 30% less than predicted to 10% larger than predicted.

We would expect a slight underestimate, since there are still some solar gains that we have not taken into account. A large spread is also quite likely since there are heat losses from one house to another through the party walls. Also, we have extrapolated from a few pressure tests up to average ventilation rates for a large number of houses.

These heat loss differences also have annual energy consumption effects. These have been estimated using a simple monthly U-value model and are shown in Table 6.7 below:-

Table 6.7 Differences in specific loss estimates and their statistical significance (derived from Table 6.6)

	Neath H - Penny 1		Penny 1 - Penny 2	
	item	signific.	item	signific.
Based on heat meter				
specific loss diff.(W/K)	12±16	none	37±4	99%
equiv. energy (kWh/yr)	780±1040	none	2410±260	99%
Based on gas meter				
specific loss diff.(W/K)	28±5	95%	38±3.5	99%
equiv. energy (kWh/yr)	1820±325	95%	2470±220	99%

As will be shown in section 6.6, the energy savings calculated from the gas meter data agree well with results from other sources. These findings are important, since they support various field trials where this kind of 'energy signature' monitoring has been undertaken. Trials such as those at Birmingham (ref. 6.5) have attempted to calculate the energy savings of retrofit insulation measures by determining the energy signature of a house before and after modification, usually with only 8-10 weeks of measurements. The Pennyland results suggest that as long as a good energy signature can be obtained (which essentially means being able to measure energy consumptions in very cold weather) the calculated energy savings are likely to be reasonably accurate.

6.3.4 Siviour's Two-Dimensional Method

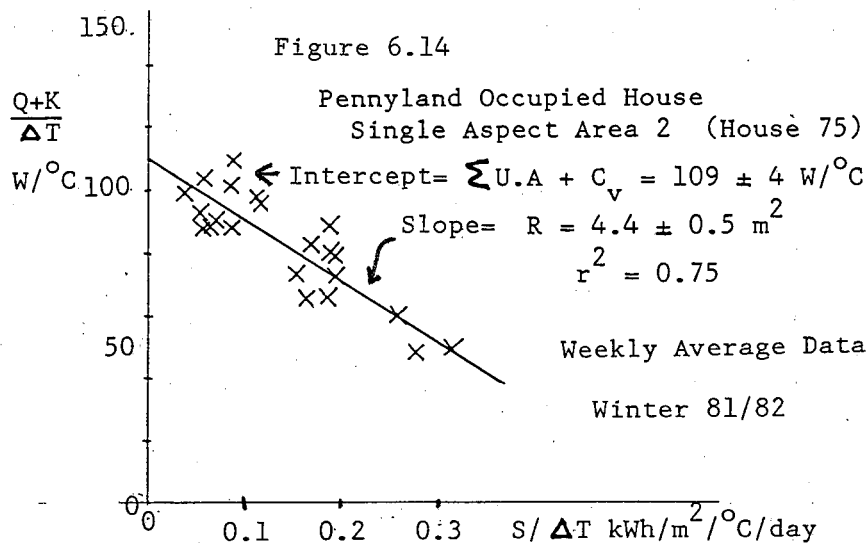
If the free heat gains, K , are known, then the heat balance equation can be rearranged in a way suggested by J.Siviour for house thermal calibration purposes (ref.6.6).

$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

transforms to

$$\frac{Q + K}{\Delta T} = \sum U.A + C_v - R.S / \Delta T$$

Thus by plotting $(Q+K)/\Delta T$ against $S/\Delta T$, we get a graph whose y-intercept is $\sum U.A + C_v$, the house total heat loss coefficient, and whose slope is R , the solar aperture. Figure 6.14 below shows such a plot for a Pennyland single aspect house:-



This type of plot has not been pursued in this project, but it has been used extensively in the Linford project. It makes a good alternative to the triaxial and 'low solar' methods, especially where good computer graphics allow the rapid drawing of graphs for visual inspection. This is very important where it is likely that the house performance is likely to be changing over the year, or as at Linford, where the floor heat loss created a large and unforeseen extra problem.

6.4 Energy Balances

Section 5.8 has already described energy balances for the intensively monitored house types. In this section we look at the self-consistency of the method. We can by making different assumptions either calculate the useful solar gains by remainder, or the house ventilation loss.

The method has built up an energy balance expressed as:-

$$\begin{array}{ccccccc} \text{Boiler} & + & \text{Incidental} & + & \text{Solar} & = & \text{Fabric} + \text{Ventilation} + \text{DHW} + \text{flue} \\ \text{gas} & & \text{gains} & & \text{gains} & & \text{loss} & \text{loss} & \text{loss} & \text{loss} \end{array}$$

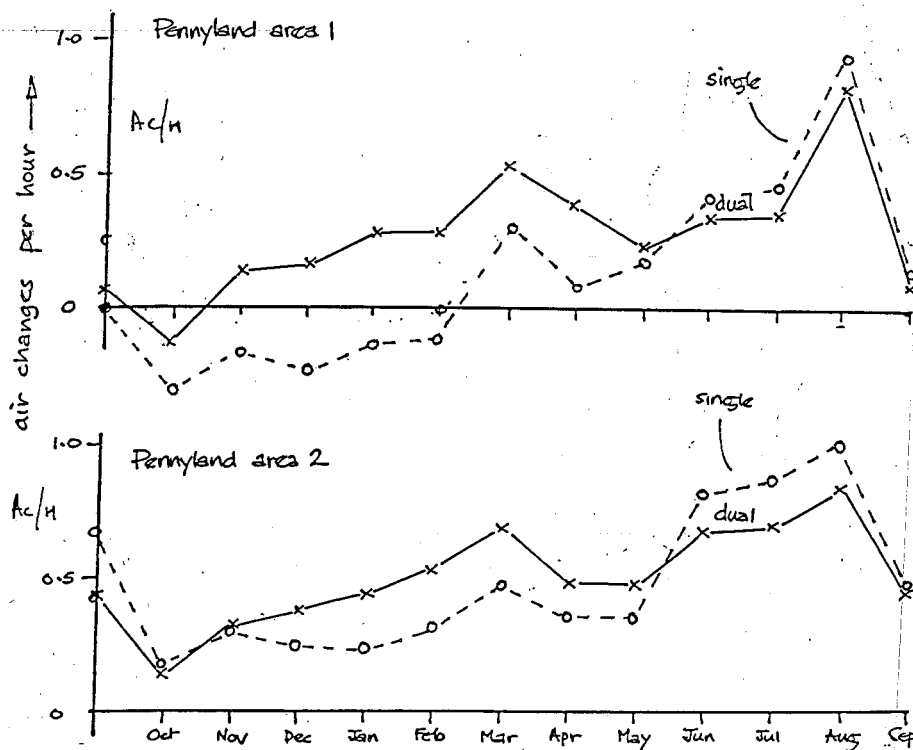
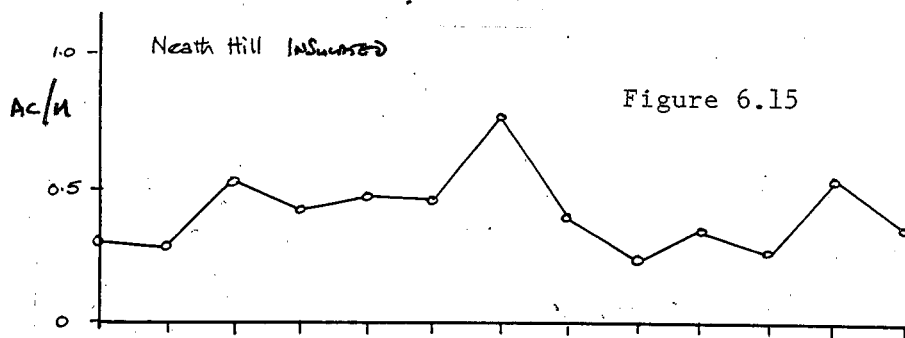
Each of these quantities could be estimated if we had information about all the others. Here we will look at estimates of solar gains and ventilation rates.

Item	Method of Estimation	
	Solar Gains as Residual	Ventilation Rate as Residual
Boiler Gas	Measured	Measured
Incidental Gains	From measured electricity, cooking, etc.	From measured electricity, cooking, etc.
Solar Gains	Residual	From regression solar aperture and incident solar
Fabric Loss	From I.H.V.E. Guide	From I.H.V.E. Guide
Ventilation Loss	From pressure tests	Residual
DHW Loss	From summer gas use	From summer gas use
Flue Loss	From sample measured boiler efficiencies	From sample measured boiler efficiencies

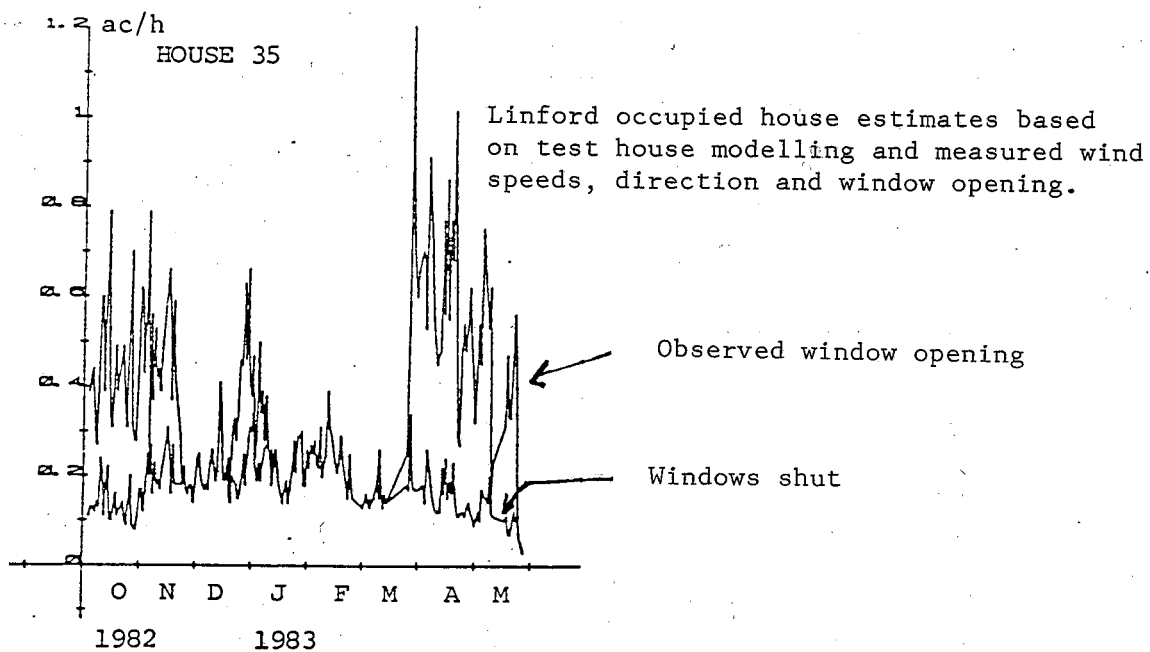
6.4.1. Ventilation rates as residual

Figure 6.15 shows the air change rates derived from the estimated ventilation heat losses as residuals. As, expected, there is a lot of 'noise' mixed up with the estimates, sometimes leading to negative values. This can be put down to measurement errors and also the presence of other factors not included, such as the floor heat loss, which as measurements at Linford have shown tends to lag about a month behind the house fabric heat loss.

The winter estimated ventilation rates are consistent with the average values assumed from pressure tests and the Pennyland data shows a distinct increase up to about 1 ac/h in summer. For comparison more detailed estimates based on Linford test house measurements and occupied house window opening data are also shown. This give a similar picture of a low winter ventilation rate rising at the end of the heating season.



Ventilation rates calculated by remainder from energy balance using fixed solar aperture.



6.4.2 Solar Gains as Residual

This method of analysis was mooted for a Europe-wide assessment survey of passive solar houses (ref.6. 7). It is thus important to understand how vague the answers are and how sensitive to other assumptions about the energy use of the house.

Figure 6.16 shows estimates of solar gains into the house both by the 'fixed solar aperture' method and by the 'residual' method. While the heating season average figures show some correspondence for each house type, the month-to-month variations seem totally clouded by noise.

The good results from the Linford occupied houses suggest that the fixed solar aperture method is likely to produce reasonable answers, at least consistent with those obtained from the test house experiments. The residual solar method relies rather dangerously on getting all the other energy flows in the house right. For example an increase in assumed air change rate of 0.25 ac/h for a Pennyland Area 2 house is equivalent to a 2.8 m² increase in solar aperture (i.e. 50%). Simplistic assumptions about ventilation rates (such as assuming 1 ac/h) would thus make total nonsense of the residual solar gains.

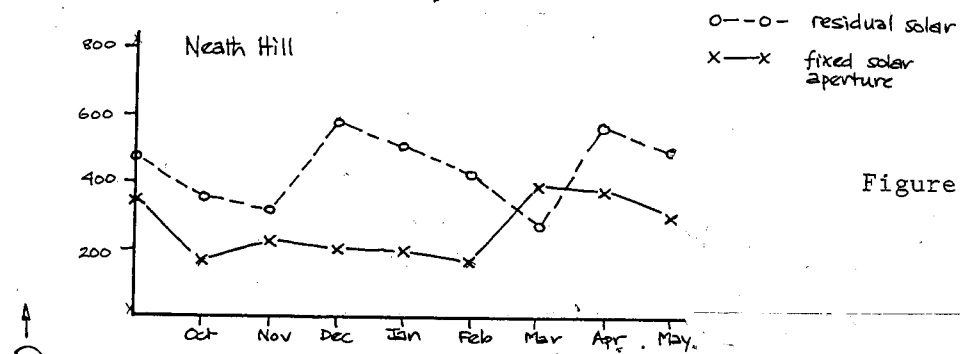
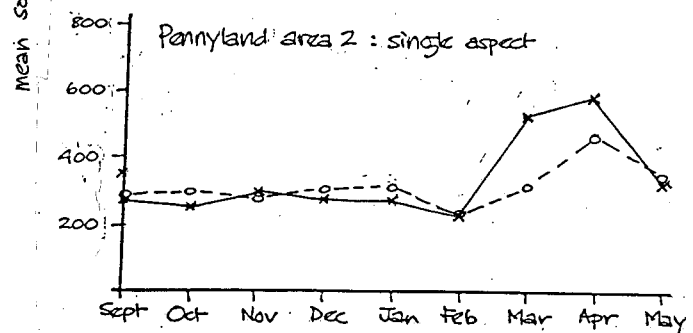
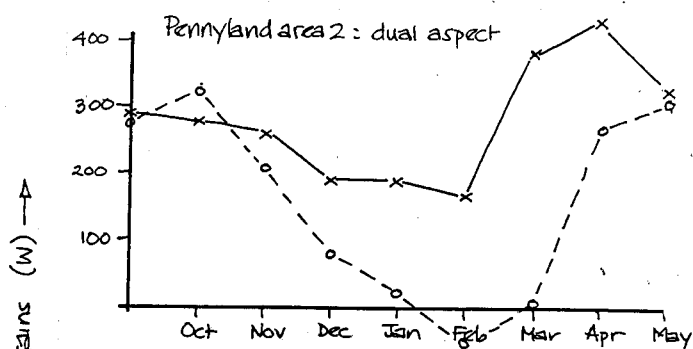
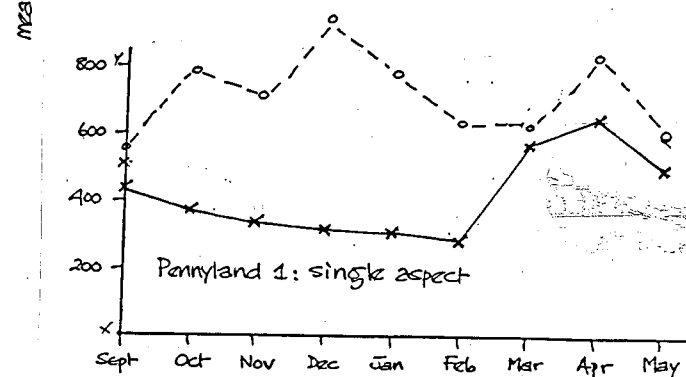
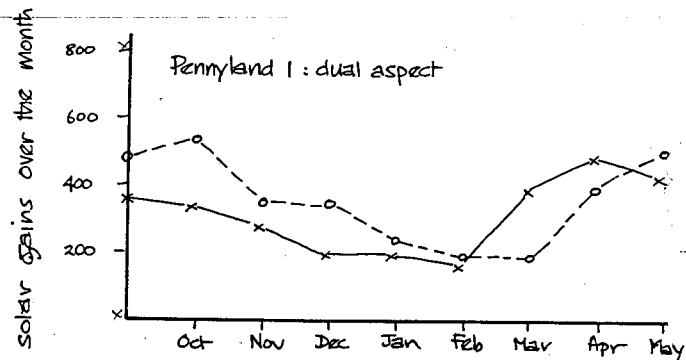
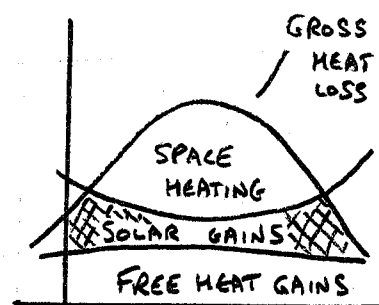


Figure 6.16



Comparisons of estimates of solar gains from the residual solar (o---o) and fixed solar aperture (x---x) energy balances.



x---x fixed aperture
o---o solar residual

6.5 Extending the Design Modelling

The Pennyland project started with a modelling and design exercise carried out over 1977 and 1978. The modelling suggested that significant energy savings would result from insulating houses to the levels of Pennyland 1 and 2 and from passive solar design measures. The exact size of these savings was however sensitive to the assumptions made about the way the houses were used, and for this reason alone were uncertain (there are also uncertainties which arise from basic limitations in the model itself).

The Pennyland and Linford projects have confirmed the crudest of the predictions of the earlier modelling work, but for a variety of reasons (as we have seen above) cannot provide answers to some of the more subtle questions. For example, the effect of the great attention that was paid to avoiding overshadowing and facing the houses south at Pennyland compared with Neath Hill is lost in a host of more important differences - heating system design, infiltration rates, room layout and the large differences between the two basic house types at Neath Hill. Nevertheless, the Pennyland and Linford projects can provide better estimates for many of the quantities eg. internal temperatures, ventilation rates, effective solar apertures, which were not well known in the first round of modelling work. By feeding estimates for these quantities based on the empirical measurements back into the modelling, we can produce a theoretical synthesis of the experimental data. In a sense this step is one of model calibration.

This synthesis can follow the comparisons originally intended, rather than having to compare 'real' house designs that may differ in several ways at once. The process is thus one of taking a 'unified' Pennyland/Neath Hill house shell through various energy saving steps to progress from the uninsulated Neath Hill house type up to the Pennyland Area 2 houses.

This step process will also be used in the next chapter to work out the cost implications of each step and the resulting cost-effectiveness.

Because of this attempt to unify the two estates there are slight discrepancies between the costing/computer modelling representation of a house shell and its real form. Some of these are in the interests of following the steps, others are due to the limitations of the NBSLD program as set up (such that it would only accept 25 mm increments of insulation thickness). Further discrepancies occur in the next chapter on costings, in the interest of producing cost-effectiveness figures relevant to current U.K. construction practice.

The savings have been calculated in three parts:-

1. Insulation and air infiltration savings from the Neath Hill uninsulated group through to Pennyland Area 2. These savings have been calculated for a 'normally overshadowed and oriented' dual aspect house. The subject of solar 'normalcy' will be discussed below.

2. Marginal passive solar energy savings, resulting from the avoidance of overshadowing, correct orientation, concentrating glazing on the south side, and the change of design from dual aspect to single aspect.
3. Boiler efficiency savings, translating the useful energy consumptions calculated above into actual gas delivered energy.

These basic steps are shown in figure 6.17

6.5.1. Insulation and Infiltration Reduction Savings

The NBSLD program has calculated the annual useful space heating consumptions for a dual aspect end-of-terrace house, taking it through the steps from the 1976 Building Regulations insulation standard up to the Pennyland Area 2 insulation level. The house is assumed to face south-west, be a true dual aspect design, i.e. with equal areas of glazing on both facades. Other details are given below:-

Element	Area m ²
External Wall	93.7
Windows	12.1
Doors	3.8
Floor/Roof	49.2

Heating 9 hrs/day - Thermostat setting 19°C
 Internal free heat gains 16 kWh/day
 Net curtains.

The weather data used for the model is Kew 1969, which has a slightly warmer average winter temperature than the Milton Keynes 81/82 data relating to the actual measurements. Solar radiation data for the two years is similar. Further details of the model will be found in reference 6.8.

For the purposes of calculation, the Neath Hill houses are assumed to have a constant ventilation rate of 0.6 ac/h and the Pennyland ones 0.35 ac/h. This choice of values perhaps slightly understates the savings assessed from pressure test results, having been taken more from Linford infiltration calculations than those given in Appendix 7. The differences are not likely to be very significant.

The calculated energy consumptions are shown in Table 6.9 and the savings between groups, in useful space heating energy, shown in a matrix form.

The table shows that the largest energy savings are due to wall insulation, with another large contribution from the reduction of air leakage. The addition of thermal mass to the design increases energy consumption, principally due to the poorer external wall U-values resulting from the use of a dense concrete inner leaf.

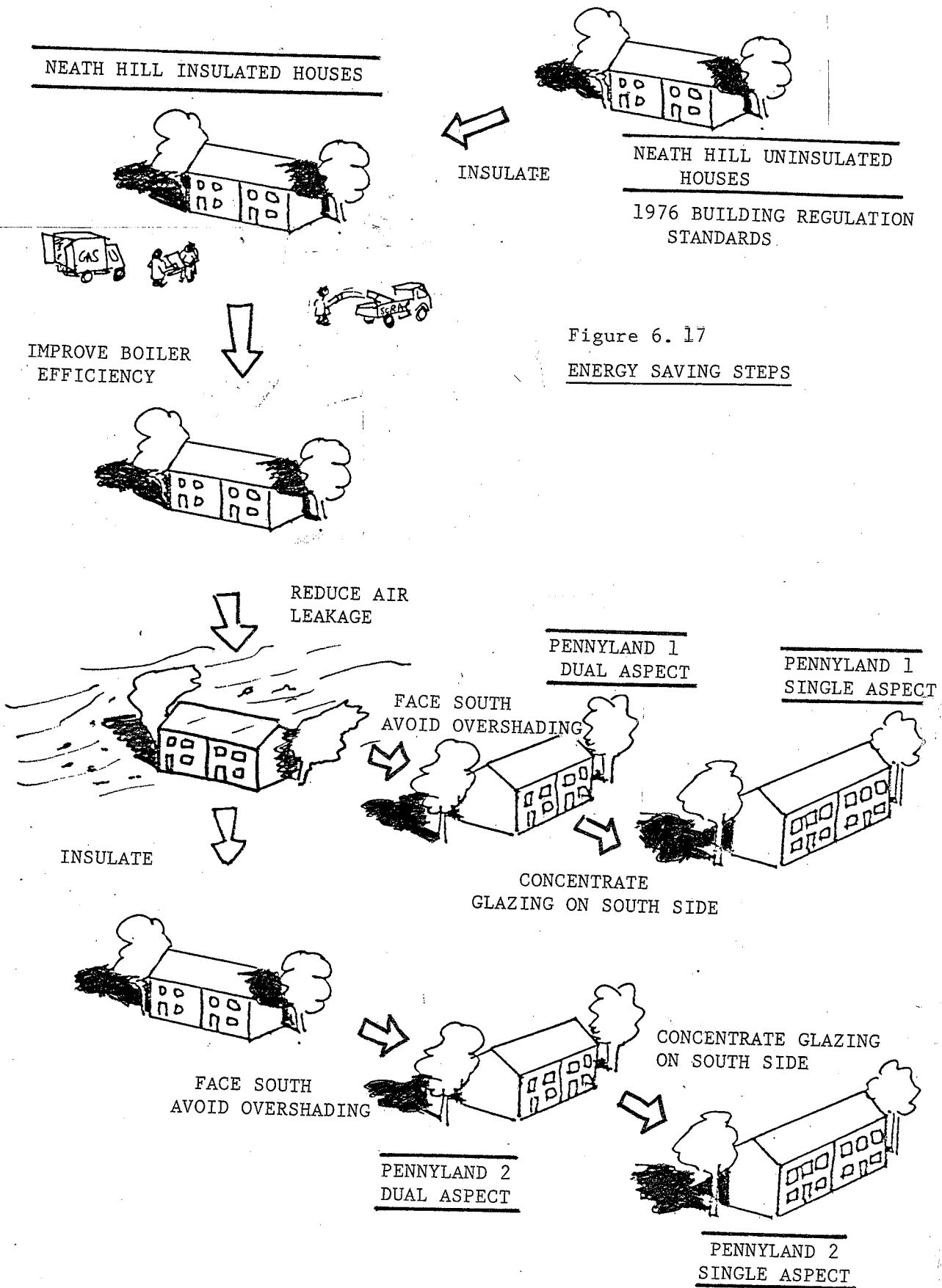


Figure 6. 17
ENERGY SAVING STEPS

Table 6.9

Pennyland reference house insulation and infiltration savings.				
	whole house heat loss W/K	fabric loss W/K	annual space heating kWh/a	useful energy saving kWh/a
Neath Hill uninsulated 1976 regulations Unfilled cavity walls 50mm roof insulation Single glazing U=4.3 W/m ² K Ventilation rate 0.6 ACH	266	216	9135	-
Neath Hill insulated. As above + 50mm wall cavity insulation	222	172	7180	1955
Add 25 mm roof insulation	214	164	6768	412
Add thermal mass	223	173	7359	-591
Pennyland Area 1. Approx 1982 building regulations Ventilation rate reduced to 0.35 ACH	202	173	6238	1121
Roof insulation 75 to 150mm	193	164	5675	563
Double glazing U=4.3 to 2.5	171	142	5055	620
Wall insulation 50 to 100mm	149	120	3907	1148
Pennyland Area 2 As above + floor edge insulation. U=0.61 to 0.46	141	112	3611	296

Insulation and infiltration savings matrix.				
kWh/a	Pennyland 2	Pennyland 1	Neath Hill insulated	Neath Hill uninsulated
Pennyland 2	0	2627	3569	5524
Pennyland 1		0	942	2895
Neath Hill insulated			0	1955

6.5.2. Marginal Passive Solar Gains

The house shell used for the insulation energy savings calculations has been taken to be 'normal' from a solar point of view. It is a little difficult to define a 'non-solar' house, especially in terms of overshadowing. In this case it has not been done with reference to the Neath Hill houses, but to a wider survey of the Cambridge housing stock carried out by the Martin Centre (ref. 6.9).

This survey was intended to evaluate the potential for retrofit passive solar measures, but is a good record of typical site conditions. It involved the analysis of hundreds of photographs taken from a height of 1.2 metres above ground in front of houses, showing the solar obstructions. The shading profiles of surrounding buildings and trees were turned into a figure for the percentage reduction in solar radiation over the assumed heating season of October to May.

Table 6.10 below shows a breakdown of average solar transmission by age and type of dwelling. For new construction, we are obviously interested in the bottom line. This shows a wide spread of values. Detached houses, in particular, are badly overshadowed and become progressively more so with age. This is almost entirely due to the surroundings of mature trees. This is likely to be the eventual fate of both the Linford and Pennyland houses. For houses with low levels of overshadowing, the obstructions are most likely to be other buildings.

Table 6.10 Overshading by Building Type and Age - Cambridge Survey

Average Percentages of received solar radiation* per type of dwelling and age group

Age Groups	Ter.	Ter.	Semi	Det.	Bung.	Fl< 5fl	Fl> 4fl	Maison.
Groups		end	det.					
Before 1900	84	86	64	51	100	93		
1900-1919	87	92	90	93	-	-	-	-
1919-1939	93	95	92	81	100	100	-	-
1939-1963	94	95	95	88	-	96	-	99
1963-1969	92	93	91	86	96	96	-	78
1970-	82	99	90	84	92	84	100	-
Average	88	93	92	81	96	94	100	86

*Received radiation = obstructed radiation/unobstructed radiation on South-facing vertical surface, October-May.

Figure 6.18

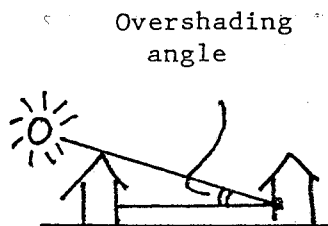
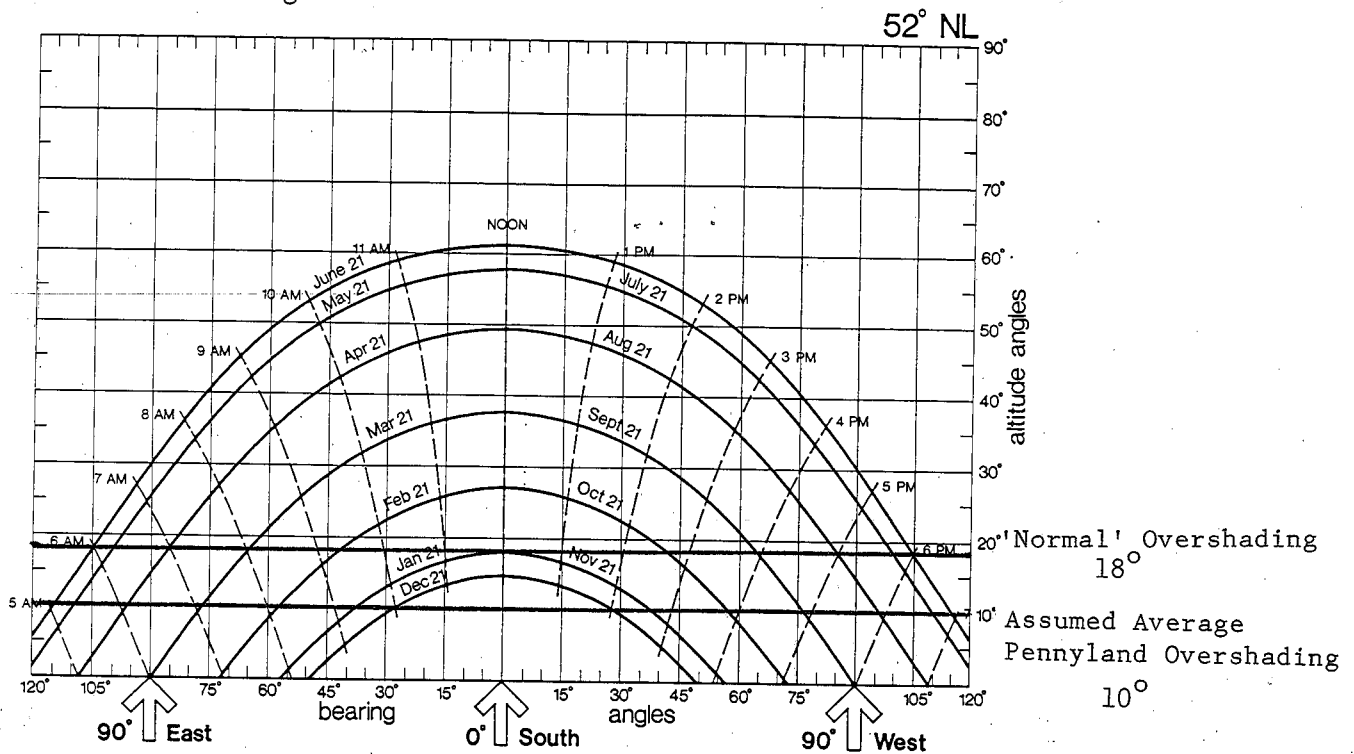
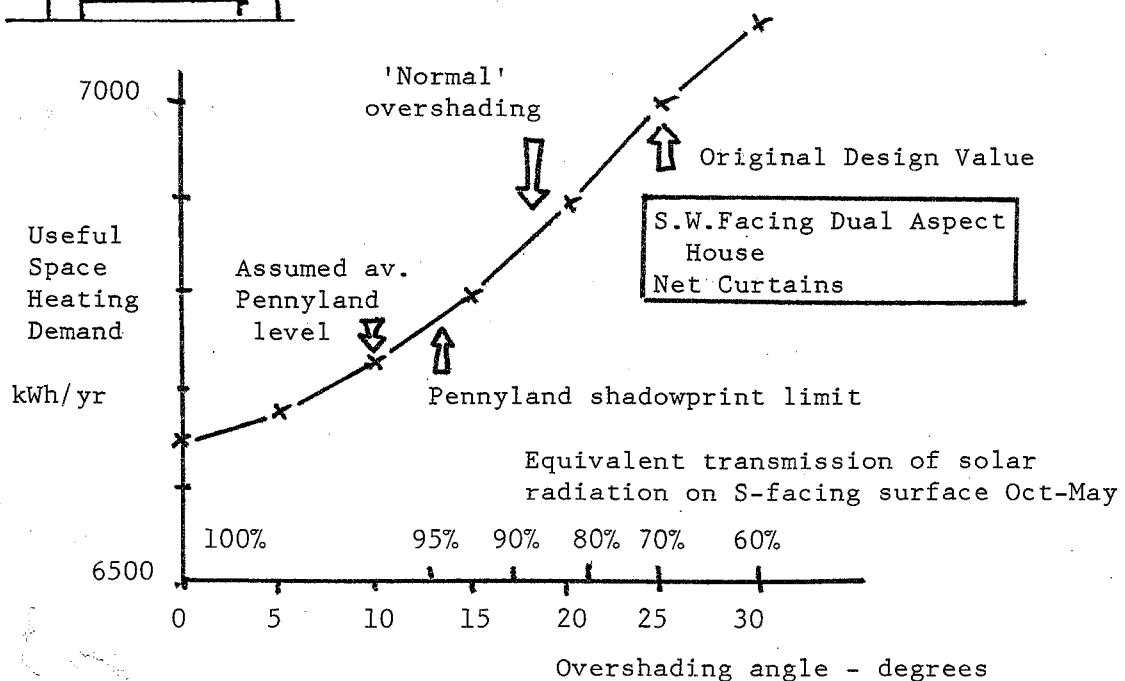


Figure 6.19
Effects of Overshading on Space Heating Demand



For the purposes of calculations, an average transmission of 90% has been taken. This corresponds to an overshadowing angle of 18° , i.e. the sun's direct rays are obstructed below this solar altitude. As shown in Figure 6.18, these means that no direct solar rays will enter the ground floor windows over a period of two months in mid-winter.

The actual Pennyland overshadowing level has been taken to be equivalent to an overshadowing angle of 10° . The design shadowprint used in laying out the estate is equivalent to an overshadowing angle of 13.5° , but most of the houses are better than this. A figure of 10° has also been used for the more extensive calculations carried out in the Linford report. In practice, it is likely that this figure will worsen over the years as the trees in the Pennyland estate mature.

Also, for calculation purposes, it has been assumed that all solar gains are effectively taken at ground floor window height and subject to overshadowing effects. Obviously solar gains to upstairs windows would not be so badly obstructed, but it is not really clear what the relative usefulness of upstairs solar gains are to downstairs ones. This is an area where modelling of a more complex nature would be useful.

The importance of overshadowing on house energy consumption can be seen in figure 6.19, showing the calculated space heating demand of a south-west facing dual aspect house as a function of the overshadowing angle and consequent percentage solar transmission. The precise definition of 'normal' overshadowing is thus quite important in making comparisons. One of the conclusions of the Cambridge survey was that overshadowing did not seem to be as bad as was originally thought. The angle of 18° used for calculations here is somewhat less than the figure of 25° taken in the original design calculations, largely from observed conditions around the Bradville solar house.

Defining a 'normal' house orientation for calculations is somewhat simpler. The calculated variation of house space heating with orientation for an overshadowed house is fairly small, (see figure 2.4), therefore for modelling purposes south-west has been taken as 'normal' orientation.

Solar absorption for the model has been based on results from the Linford test house. Here tests were carried out to determine the effective solar aperture of the house with and without net curtains and before and after insulating the ground floor slab. Solar gains were generally somewhat less than originally estimated due to considerable reflection from the interior of the house.

For the purposes of calculation all houses have been taken to have full net curtains with appropriate levels of solar gains.

The almost universal use of net curtains in the Pennyland estate has been a source of much disappointment. A glance at the various photos of the houses in this report will show that nearly all the windows appear white and not black. Most are actually lighter than the surrounding brickwork, implying a solar absorptance of 50% or less.

Even worse, there was an extensive tendency for blinds and shutters to be left drawn on sunny winter days. For example, in the photograph figure 2.6, there are six windows visible. Only one is unobstructed, three have full net curtains and two have the paper blinds firmly drawn.

In the social survey, 35% of Pennyland residents admitted to drawing blinds or shutters on sunny winter days. A count of windows made in March 1983 showed that 80% had full net curtains and less than 10% had no obstruction at all.

It is likely that this level of window obstruction is partly a glare problem—that could perhaps be dealt with by better window design, but mostly a privacy one. The fact that photographs such as figure 6.20 can be easily taken from the street or public pathway makes this clear.

The Linford houses, which are not overlooked from the south had only a 50% use of net curtains and consequently higher solar gains. Dealing with this privacy problem in estate design would probably increase the solar gains but might be extremely difficult to engineer.

Energy Calculations

The NBSLD program has been used to assess five house types at the two different Pennyland insulation levels:-

- House A. True dual aspect house shell with equal glazing on both facades. Net curtains. 'Normally overshadowed', faces S.W.
- House B. As above but south-facing and with reduced overshadowing. Overshading angle 10° .
- House C. Pennyland dual aspect house design. As above but with 1.35 m^2 of window area brought from the north facade to the south. North facing window area 4.7 m^2 , south 7.4 m^2 .
- House D. Pennyland single aspect design. Same floor area as dual aspect design, but built to a shallow plan with more total glazing area and most concentrated on the south facade.

External wall area	88.8 m^2
South-facing window area (including glazed door)	13.6 m^2
North facing window area	3.9 m^2
Unglazed door area	3.9 m^2
Net curtains	
Other details as above	

- House E. Pennyland single aspect design but with no window clutter.

The energy consumptions of these different house types are shown in Table 6.10 together with the savings expressed as a matrix form.



Figure 6.20

The presence of net curtains (upper floor) or drawn blinds (downstairs right) dramatically reduces the window solar absorptance. Less than 10% of south-facing Pennyland windows had no obstructing curtains.

Table 6.10

Passive solar design savings.					
House type	Area 1		Area 2		
	aux space heat kWh/a	saving kWh/a	aux space heat kWh/a	saving kWh/a	
A. True 'dual aspect' S.W. facing, over- shaded, net curtains	6238	-	3611	-	
B. True 'dual aspect' South facing, reduced overshading, net curtains	6052	186	3442	169	
C. Pennyland dual aspect South facing, reduced overshading, net curtains	5937	115	3354	88	
D. Pennyland single aspect South facing, reduced overshading, net curtains	5957	-20	3345	9	
E. Pennyland single aspect South facing, reduced overshading, no window clutter	5621	336	3104	241	

Solar savings matrix. Pennyland area 1 insulation.					
	A	B	C	D	E
B	186	0			
C	301	115	0		
D	281	126	-20	0	
E	617	431	316	336	0

Solar savings matrix. Pennyland area 2 insulation.					
	A	B	C	D	E
B	169	0			
C	257	88	0		
D	266	97	9	0	
E	507	338	250	241	0

The marginal solar savings of the Pennyland dual aspect houses in relation to the 'normal' Neath Hill houses amounts to about 300 kWh/yr of useful space heating energy. Of this about 200 kWh/yr is due to the avoidance of overshadowing and correct orientation and 100 kWh/yr due to the slight shift of glazing from the north facade to the south. These results apply at both Area 1 and Area 2 insulation levels.

There will also be very slight increases in average internal temperatures as a result of these changes, but these have not been assigned any usefulness by the program.

There appears to be no difference in energy consumption between the single and dual aspect types. Although the single aspect houses have larger solar inputs, these are just used to offset the increased heat loss of the design.

Comparison with original estimates

These results are considerably less than originally estimated. The avoidance of overshadowing and correct orientation were originally estimated to save 700 kWh/yr of useful space heating. The large reduction is due to both the low solar absorptance due to the use of net curtains and the redefinition of 'normal' overshadowing.

The original estimate of the dual aspect-single aspect difference was 200 kWh/yr. The fall to zero is simply due to the lower solar absorptance. Marginal passive solar gains could still potentially be reasonably large, as demonstrated by the 'reduced window clutter' figures. There is potentially an extra 300 kWh/yr for a single aspect house type if only windows could be made good solar absorbers.

These figures are, of course, totally dependent on the solar absorption figures measured in the Linford test house and any errors made there will affect these answers. For details of these measurements and the problems involved, readers are referred to the Linford project report.

6.5.3 Boiler Efficiency Savings

Finally, the useful space heating figure from tables 6.9 and 6.10 are brought together with an assumed useful water heating consumption of 2850 kWh/yr and the boiler efficiency plots of figure 6.21 to give the total house boiler gas energy consumptions.

For ease of tabulation the boiler standing losses (pilot light, etc.) have been expressed as an equivalent useful energy which can then be converted to delivered energy by multiplying by the marginal boiler efficiency.

Table 6.11 shows the total delivered energy consumptions of the various house types and the reductions in house heat loss accompanying them. These figures will then be taken forward into chapter 7.

The contents of Table 6.11 are plotted in figure 6.22, basically in useful energy, but convertible into delivered energy by using the left and right hand scales.

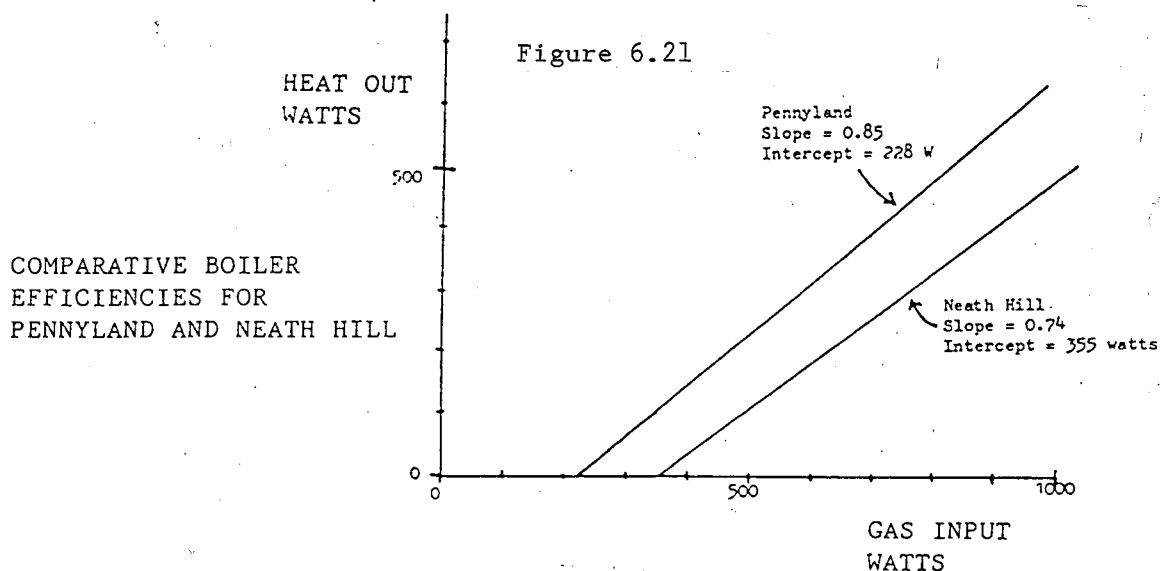


Table 6.11

PENNYLAND ENERGY
SAVINGS

All units are
kWh/yr

Useful Space Heating	9135	7180	7180	6768	7359	6238	5947	5621	5675	5055	3907	3611	3345	3104
Water heating & tank losses	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850
Boiler standing losses	2300	2300	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700
Total Equivalent Useful Energy	14285	12330	11730	11318	11909	10788	10547	10211	10225	9605	8457	8161	7895	7701
Total Delivered Energy	19304	16662	13800	13315	14010	12691	12408	12012	12029	11300	9949	9601	9288	9060
Delivered Energy Saving	-	2642	2862	485	-695	1319	283	396	661	729	1351	348	313	228
Reduction in Fabric Heat Loss W/°C	-	44	-	8	-9	-	-	-	9	22	22	8	-	-

Neath Hill
Uninsulated

Neath Hill
Insulated

Boiler

Roof Insulation
50mm-75mm

Add thermal
mass

Reduce vent.
rate

Pennyland 1
+ Marg. solar gains

Reduce window
clutter

Roof insulation
to 150 mm

Double glazing

Wall insulation

Floor insulation

Pennyland 2
+ Marg. Solar Gains

Reduce window
clutter

← 74% →
marginal efficiency

85%
marginal efficiency →

COMPUTED ENERGY SAVINGS FOR A DUAL ASPECT
END-OF-TERRACE HOUSE

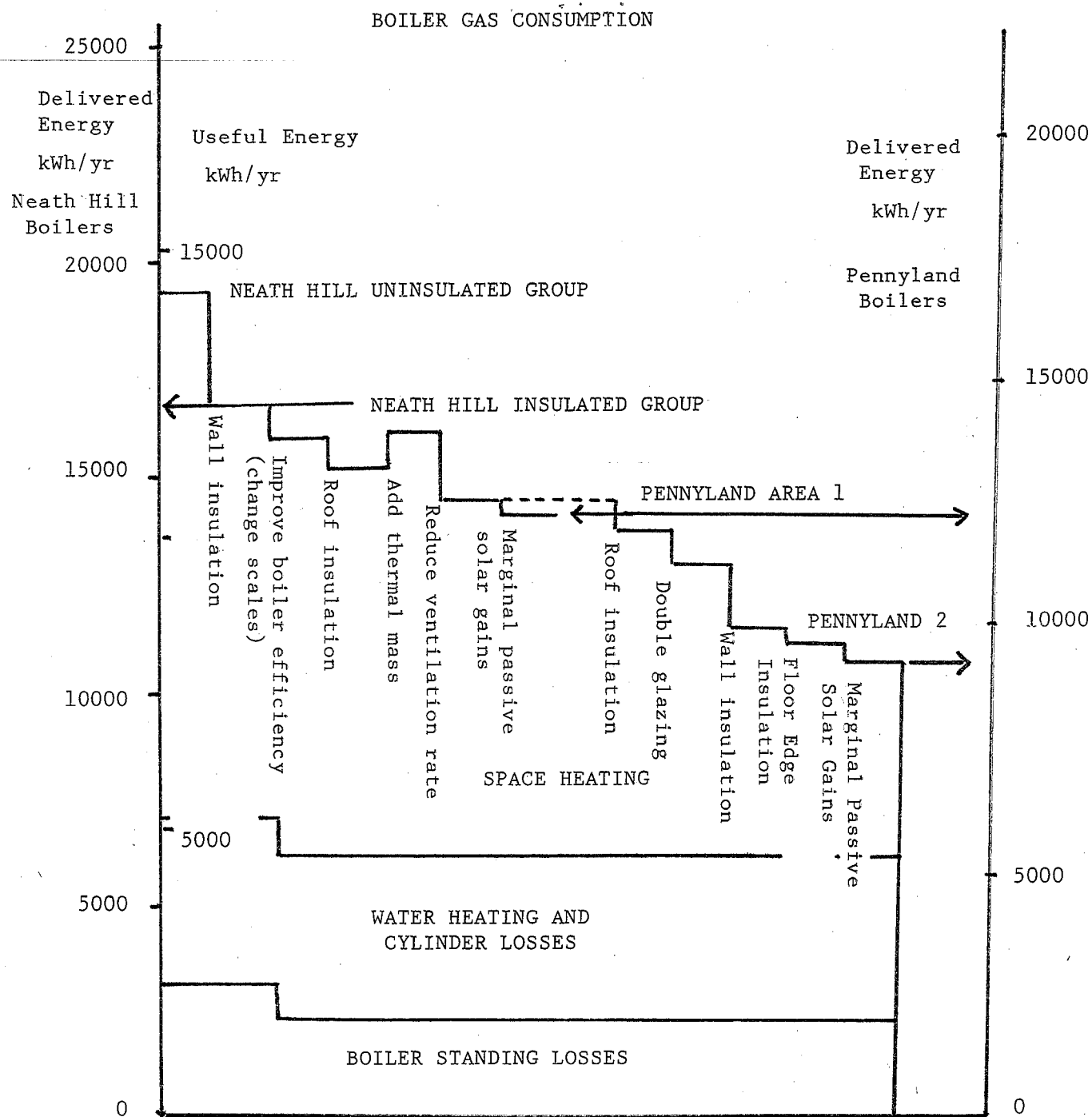


Figure 6.22

6.6 Summary and Comparisons of Energy Savings

This section is an attempt to reconcile the modelling and experimental results. This is in order to provide the most credible estimates of energy savings which will be used to work out the cost-effectiveness in the next chapter.

In this chapter energy savings have been calculated by a variety of methods:-

1. Refined and statistically processed annual gas consumptions
2. Modelling using the updated NBSLD design model.
3. Simple modelling from measured differences in the house heat losses.

Results from the first two methods will be taken forward into the next chapter.

6.6.1. Credibility of NBSLD model

First it is necessary to assess the credibility of the NBSLD model in producing similar annual energy consumption figures to those measured. Unfortunately, time did not permit the production of a suitable hourly weather data file for 1981/82. This would have allowed the NBSLD model to be used with the same weather data as applies to the actual measurements. It has instead been necessary to use the Kew 1969 weather data used in the original design process. The winter of 81/82 was slightly colder than the Kew data, with about 200 more degree-days. This temperature difference requires a correction of about 1000 kWh/yr to the computed space heating estimates.

Comparisons of modelling and measurement for the Linford project have shown that getting good agreement within about 1000 kWh/yr is very difficult. Occupant behaviour has a very large effect and it is difficult to describe in a simple way suitable for a model. For example free heat gains from cooking, lighting, etc., are not constant over the year, but tend to peak in mid-winter (see Linford report). Ventilation losses may vary enormously over the heating season with window opening.

Figure 6.23 shows computed and measured estimates of annual space heating consumption for the five intensively monitored house groups. The agreement is fairly close, considering statistical uncertainties. The minor differences in energy savings between groups will be dealt with below.

Figure 6.24 shows computed and measured annual gas consumptions for the four main insulation groups. The computed values, taken from Table 6.11 have been given an additional 1000 kWh/yr average gas cooking consumption. Again the agreement is reasonable considering the statistical spreads.

The detailed credibility of the NBSLD model as used in this project, is mostly dependent on the Linford project results. No formal 'validation' has been carried out, since this is an enormous task, but the model has demonstrated an ability to produce similar energy flow patterns to those actually measured.

Figure 6.23

Comparison of Measured
and Computed Space
Heating Demands

Measured data corrected
to common internal
temperature



Predicted from
NBSLD model with
correction for
degree-day difference

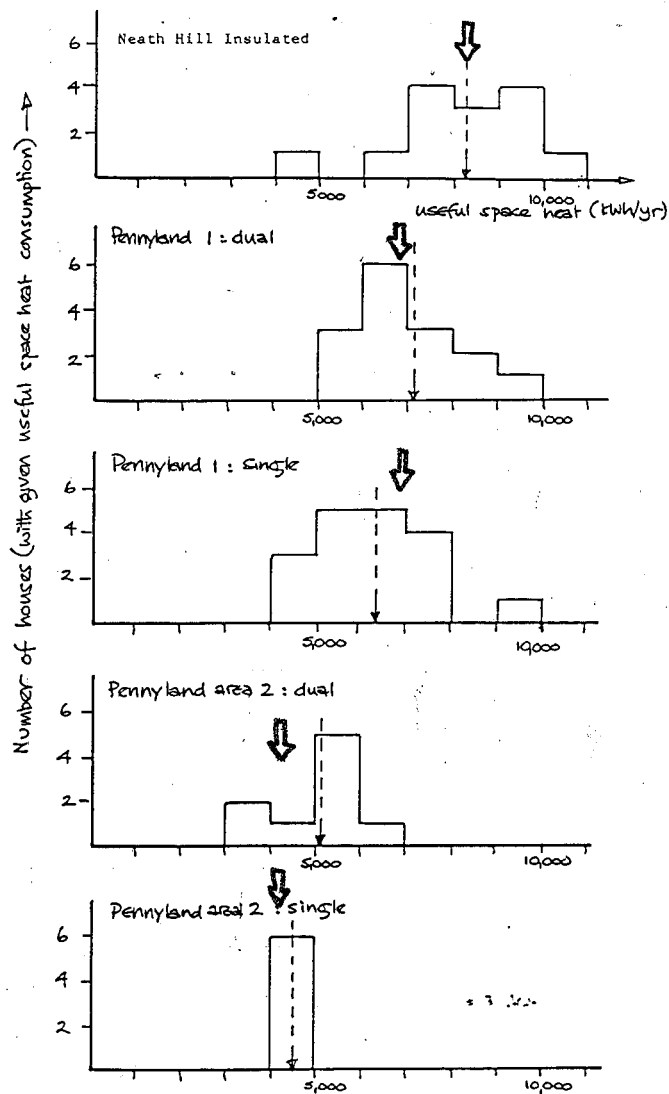
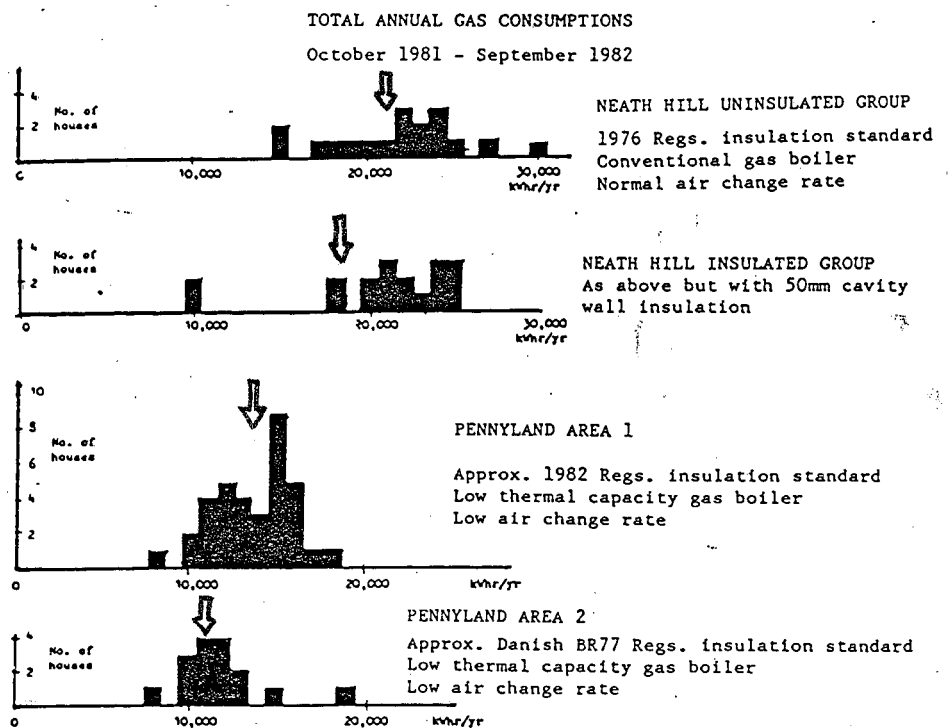


Figure 6.24

Comparison of
Measured and
Computed Annual
Gas Consumptions



Predicted from
NBSLD model
corrected for
difference in
degree days
and cooking use.



6.6.2. Summary of Energy Savings

We can now bring together the various estimates of the energy savings between the groups, made by different methods and with different assumptions. These savings with their standard errors (i.e. 70% confidence limits) are shown in figure 6.25. The 95% confidence limits are at approximately twice the standard error spread.

Neath Hill Uninsulated - Neath Hill Insulated

Saving from annual gas consumptions	2500 \pm 1700	kWh/yr delivered
Saving from NBSLD model	2642	kWh/yr delivered

This is a poorly controlled comparison since the only data available on the uninsulated group is quarterly gas bills. The main aim of the comparison was to check on the 'normalcy' of the Neath Hill Insulated group, but there is a high probability of a genuine energy saving.

Neath Hill - Pennyland Gas Boilers

Savings from measured efficiencies and consumptions	3400 \pm 1300	kWh/yr delivered
Savings from measured efficiencies and computed consumptions	2862	kWh/yr delivered

This saving is the large single one in the whole project. Although there is a fairly large standard deviation associated with this estimate, we have fair confidence in the result because of the good agreement with British Gas boiler studies. The difference in energy saving between the two estimates is due to slightly different assumptions of hot water use and the warmer weather data used in the NBSLD model.

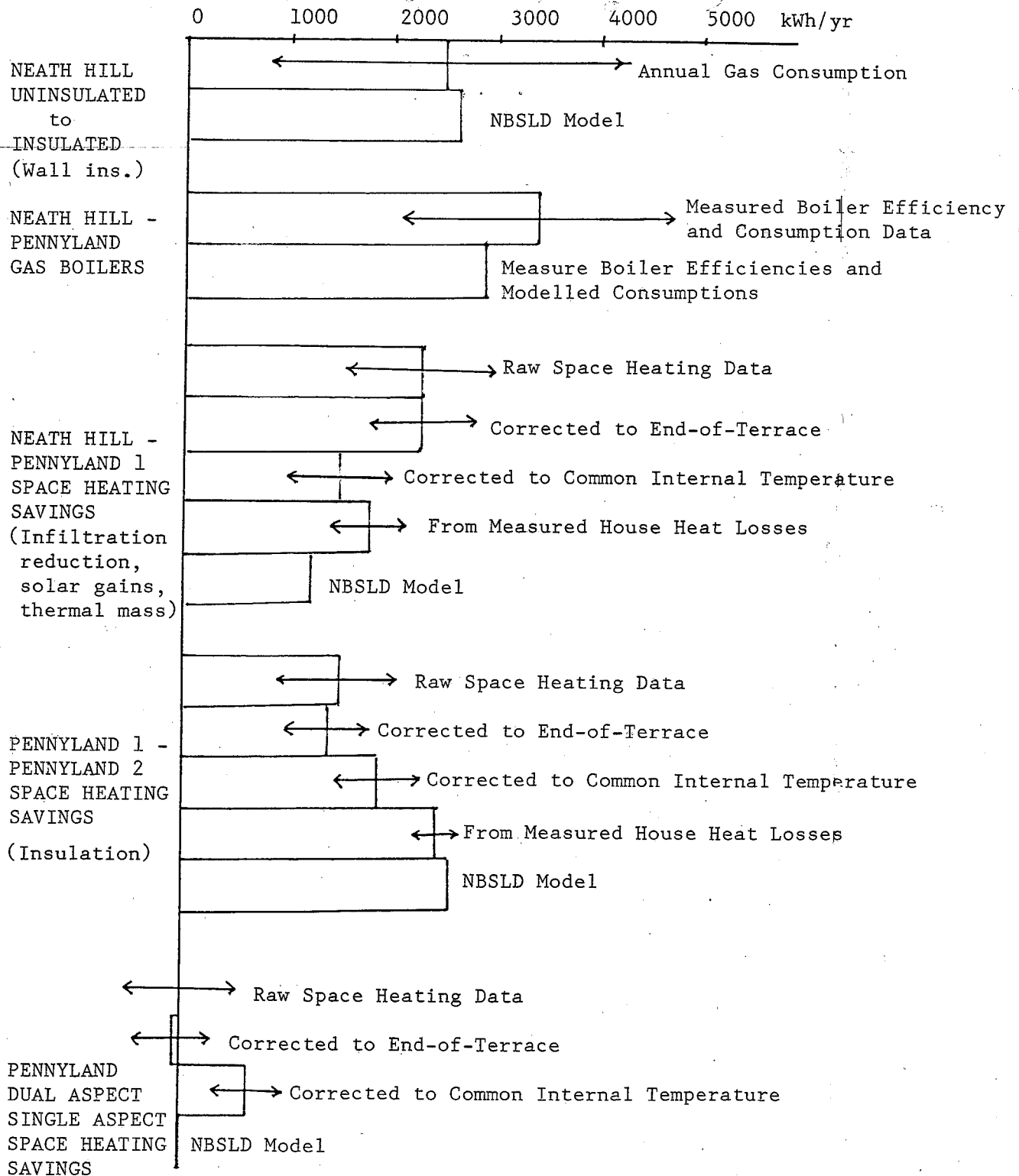
Neath Hill - Pennyland 1

		kWh/yr useful
Annual space heating analysis	- raw data	2300 \pm 720
	- corrected to end-of-terrace	2300 \pm 490
	- corrected to common temperature	1500 \pm 490
From measured house heat losses		1820 \pm 325
From NBSLD model		1233

In the original design estimates, this step was expected to produce a saving of about 700 kWh/yr, just due to the avoidance of overshadowing and correct orientation. In practice, the large difference in boiler efficiency and air change rate have made this step extremely difficult to analyse. Given the large uncertainties in hot water use and cooking consumption it is not possible to draw any firm conclusions as to whether such a solar contribution exists or not.

The Neath Hill houses had higher winter average internal temperatures than the Pennyland Area 1 houses, hence the large estimate of energy saving in the raw data and from measured house heat losses. These estimates reduce when an assumption of equivalent internal temperatures is imposed, both in correcting the raw data and in the NBSLD model.

Figure 6.25 ESTIMATES OF ENERGY SAVINGS BY DIFFERENT METHODS



68% Confidence range

(95% confidence range approximately double this)

Pennyland 1 - Pennyland 2		useful kWh/yr
Annual space heating analysis	- raw data	1500 \pm 560
	- corrected to end-of-terrace	1400 \pm 400
	- corrected to common temperature	1900 \pm 400
From measured house heat losses		2450 \pm 220
From NBSLD model		2602

Since the Pennyland Area 1 houses had lower internal temperatures than either Neath Hill or Pennyland Area 2, the energy savings from the raw data are on the low side, the benefits of the extra insulation in Pennyland 2 being taken as extra temperature. Correcting the data to a common temperature increases the estimated energy savings as the extra temperature is now expressed as equivalent energy use. This also brings the measured estimate closer to that calculated using the NBSLD model (which approximates to a common internal temperature) and the estimate from the measured house heat losses.

The energy saving produced by this step is fairly important to determine accurately, since it is the one that relates to the benefits of introducing the Danish BR77 regulations in the U.K. There is no way of telling whether the increased internal temperature in Area 2 is useful or not, but for the purposes of cost-effectiveness calculations in the next chapter it has been assumed that they are. There certainly appears to be a higher degree of satisfaction with heating performance in Area 2.

Dual Aspect - Single Aspect		useful kWh/yr
Annual space heating analysis	- raw data	0 \pm 550
	- corrected to end-of-terrace	-90 \pm 350
	- corrected to common temperature	670 \pm 350
From NBSLD model	- Pennyland 1	-20
	- Pennyland 2	9

Here the results are fairly conclusive. Given the designs of the houses used at Pennyland the space heating difference appears to be about zero, in line with the results of the NBSLD model.

The single aspect houses appear to be slightly warmer than the dual aspect ones. Unfortunately, some or all of this difference may be due to the positioning of the external temperature sensors, rather than to a real difference in internal temperatures (see section 4.4.1). If all of the difference were real, and if all of it were useful, then it would be worth about 700 kWh/yr in energy terms.

6.7 Wider Comparisons with Other Houses

The energy savings of both this and the Linford project have been calculated using a sample of 18 houses on the Neath Hill estate (the uninsulated group), to represent 'Brand X', the normal British house. The Neath Hill houses can in no way be described as a deliberate choice of poor quality houses picked to make the Pennyland performance look artificially good. The Neath Hill estate was the show estate of Milton Keynes for 1978 & 79 and was deliberately built and detailed to high standards because of the poor reputation of some of the previous Milton Keynes estates.

However, this sample of 18 houses can hardly be taken to represent the rest of modern U.K. housing without some further comparisons. Two ways of extending the project to wider surveys have been used:-

1. A comparison with annual gas consumptions on four other Milton Keynes estates for the winter of 1975/76.
2. A comparison of boiler gas consumptions with 'McNair's Equation', a simple relation between fuel use, number of occupants, house heat loss and degree days, produced by British Gas.

6.7.1. Other Milton Keynes Data

During the Bradville active solar house project, the question was raised of whether or not the energy use of the occupants was 'normal'. This was very important since the energy output of the active solar system was very dependent on the heating demand, with consequent effects on its cost-effectiveness. The Pennyland project poses the same question as to whether the Neath Hill uninsulated houses can be regarded as 'normal'.

In answer to the Bradville solar house question, and as part of the design studies for the Pennyland project, annual gas and electricity consumptions for 5-person houses on nine Milton Keynes estates were gathered. The results for the four estates with full gas central heating for space and water heating are shown below:-

Estate	Delivered Energy	
	Gas	Electricity
Bradville 1	24348	2189
Fullers Slade	23674	2086
Stantonbury 1	18576	2003
Windmill Hill	22121	2841
Average	22172	2416

Table 6.12

This data was gathered for the period March 1975 - February 1976 (with slight variations due to precise meter reading dates) and in the interests of consumer privacy only average digests were prepared.

The houses in the four-estate sample (about 150 in all) were all built to the 1975 building regulation standards and thus differ from the Neath Hill houses in only requiring 25 mm loft insulation rather than 50 mm.

This would imply an extra energy consumption of about 1500 kWh/yr of delivered energy. Fortunately this amount is almost exactly offset by the fact that the 75/76 weather was slightly warmer than the 81/82 period used for the main Pennyland comparisons by about 100 degree-days. This makes the consumption figures reasonably comparable. The table below shows the Pennyland and Neath Hill figures compared to the 4-estate sample:-

Sample	No. of Houses	DELIVERED ENERGY			
		Gas		Electricity	
		kWh/yr	£/yr*	kWh/yr	£/yr*
M.K. 4-Estate Sample (75/76 Data)	150	22172	253	2416	121
Neath Hill Uninsulated	18	23400	267	Not Measured	
Neath Hill Insulated	14	22480	256	3086	154
Pennyland 1	33	14010	160	2856	143
Pennyland 2	15	11530	131	2598	148

Table 6.13

*Spring 1984 prices

This table clearly reinforces the overall picture of a halving of annual gas consumption across the project, but with little change in annual electricity consumption.

Comparisons have been made between the measured winter internal temperatures in the Bradville solar house and its energy consumption in relation to similar houses in the rest of the estate (see ref.6.10). These would imply quite high internal temperatures in the rest of the estate (17-18°C), though a sample of one is not really much to go on.

6.7.2 McNair's Equation

Another wider comparison that can be made is with a simple empirical equation produced by Peter McNair of British Gas. (ref 6.11)

This aims to estimate annual central heating gas consumption as a function of house fabric heat loss, no. of occupants and degree-days. The formula is based on the analysis of 96 houses over a wide range of types and locations. The equation is similar in form to that used in the statistical analysis in section 6.2.

In fact the equation was developed for similar purposes, to improve the estimates of the differences in energy consumption between houses heated with individual central heating systems and those heated using district heating. It should also be pointed out that the coefficients are subject to the same large statistical ranges as those produced for section 6.2. (see ref. 6.12)

$$\begin{aligned}\text{Annual Heating Gas Consumption} &= 61 + (70.\text{DHL}.\text{DD}/2222) + 59.\text{N} \text{ Therms/yr} \\ &= 204 + (234.\text{DHL}.\text{DD}/2222) + 197.\text{N} \text{ Mean Watts}\end{aligned}$$

where DHL = Design Heat Loss in kW
 DD = No. of degree-days to base 15.5°C
 N = No. of occupants

The design heat losses have been calculated on the basis of the following internal temperatures and air change rates, with a design external temperature of -1°C.

	°C	ac/h
Living/dining room	21	1.5
Kitchen/W.C./Hall	18	2.0
Bedrooms	16	0.5

The resulting average design heat losses for the Pennyland and Neath Hill houses are given below, with the average number of house occupants:-

	DHL kW	No. of occupants
Neath Hill Insulated	5.2	3.4
Pennyland 1	5.1	3.2
Pennyland 2	4.0	3.0

The weather data for the monitored period totalled 2271 degree-days, very close to the 'standard' U.K. value of 2222 used in the equation.

Feeding these values into the equation allows us to compare estate average predicted heating energy consumptions with those actually measured:-

	Annual Boiler Gas Consumption kWh/yr	
	Predicted	Measured
Neath Hill Insulated	18571	20901
Pennyland 1	18080	13166
Pennyland 2	15365	10906

These predicted and measured results are shown on a house-by-house basis in figure 6.26.

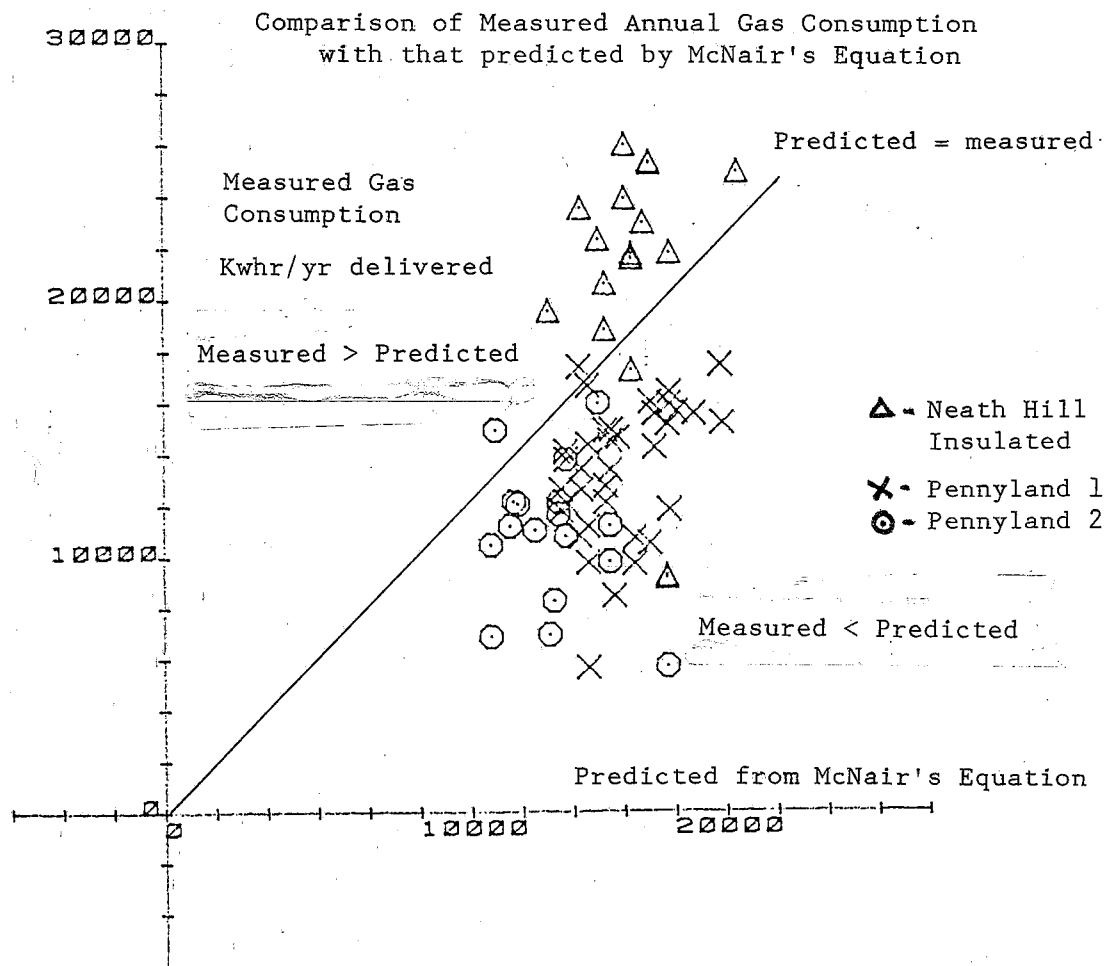
Conclusions

It would appear from these results that the Neath Hill houses are about 20% worse than predicted and the Pennyland houses 20-25% better than predicted.

There are fairly plausible reasons for this:-

1. The Neath Hill houses have possibly slightly higher internal temperatures than other U.K. houses at this insulation level.

Figure 6.26



2. The Neath Hill houses seem to have a higher hot water heating use than average for reasons that are not really clear.
3. The prediction formula makes no allowance for boiler efficiency or house airtightness, hence the good Pennyland performance.

At first sight the Pennyland result seems surprising, since it would seem that there ought to be some law of decreasing returns on energy conservation at high insulation levels. If there is such a law, it does not seem to set in until even higher levels of insulation than Pennyland Area 2 have been reached.

The large measured energy difference between the Neath Hill insulated houses and the Pennyland 1 group, given similar predicted energy consumptions, does indicate that the mere specification of a house heat loss is no real guide to its energy use. This came as somewhat of a surprise to the researchers on this project, though the reasons are now obvious. This does indicate the need for a better way of phrasing Building Regulations in terms of overall energy performance.

6.8 Conclusions on Energy Savings

Although there has been much discussion of the sources of uncertainty and the difficulties in drawing firm conclusions from the project, it should be remembered that overall the Pennyland Area 2 houses consume about a half of the annual gas consumption of the Neath Hill Uninsulated group, or for that matter a large selection of Milton Keynes houses built only a few years previously.

There is no doubt that a substantial energy saving has been achieved. Indeed the basic statistical data indicates a very high level of confidence in both the saving between Neath Hill and Pennyland and between the two halves of the Pennyland estate. In terms of convincingly demonstrating energy savings, this has probably been the most successful housing field trial conducted in the U.K.

There is good evidence, both from the pressure test measurements and annual energy consumptions that the Pennyland houses have a significantly lower ventilation rate than the Neath Hill houses. There have not been enough tests to determine whether there are significant differences between the two halves of the Pennyland estate.

There is a considerable confidence in the savings associated with the use of low thermal capacity boilers. This is supported by the detailed analysis work carried out on the Linford project.

Apart from an apparent increase in effective solar aperture, determined by weekly regressions, there is not much evidence that the Pennyland dual aspect houses are any better at using solar energy than the Neath Hill ones. The solar comparisons originally intended have been clouded both by the basic statistical problem and unforeseen differences such as the large changes in air leakage and boiler efficiency between Neath Hill and Pennyland. The solar answers, such as they are, have largely been produced by adjusting the design computer model using the results of the Linford test house measurements.

Regression analysis suggests that the single aspect houses have a higher solar energy input than the dual aspect ones, in line with their larger south-facing glazing area. This is not reflected in their raw space heating consumptions and it appears that the extra solar input merely offsets the larger heat losses of the single aspect design.

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CHAPTER 6

DETAILED ANALYSIS

CONTENTS

- 6.1 Overview of Methods of Analysis
- 6.2 Statistical Analysis of Annual Space Heating
- 6.3 House Characterisation
- 6.4 Energy Balances
- 6.5 Extending the Design Modelling
- 6.6 Comparison of Measurements and Modelling
- 6.7 Wider Comparisons

This chapter examines the data in more detail, refining the group energy comparisons, determining the solar gains and using computer modelling to produce best estimates of the project energy savings.

"I have yet to see any problem, however complicated, which when you looked at it the right way, did not become still more complicated".

Poul Anderson.

6. DETAILED ANALYSIS

6.1. Overview of the Methods of Analysis

The Pennyland project has generated a vast amount of data on the energy consumption in 170 houses. As explained in the previous sections the simple comparisons, planned when the project was designed, no longer make much sense. There is a much wider range of house types and sizes than initially conceived and the Neath Hill control has proved to be so different from the Pennyland estate in several important respects that it cannot serve as a control against which to measure solar contributions. To make this clear it should be noted that the extra solar gains from the passive solar design are expected to be less than 1000 kWh/yr. The observed difference between Neath Hill and Pennyland is about 8000 kWh, of which 3000 kWh can be attributed to additional boiler losses, about 1500 kWh to differences in ventilation rates, perhaps another 1500 kWh due to differences in mean temperatures and about 2500 kWh to differences in water heating. All these estimates of differences are liable to considerable uncertainty, which, coupled with the inevitable variations between houses and the small sample sizes, means that there is no hope of identifying any residual difference of less than 1000 kWh by simply comparing annual or weekly fuel consumption figures.

Although the simple approach won't work it is possible to undertake more sophisticated analyses of the data available and attempt to obtain estimates of the solar contributions in other ways. All these additional methods of analysis introduce some additional knowledge, theory or data in order to reduce one or more sources of variation with the aim of leaving the differences we are seeking more apparent. We know that there are large differences in total energy consumption between the houses, as indicated in Figure 6.1. The question is "what are the factors causing these differences?" We know that there are random differences between the houses due to the different patterns of occupancy (different temperatures, ventilation rates, uses of appliances and hot water etc). We also expect there to be differences caused by differences in fabric loss due to both different levels of insulation and differences in levels of terracing (i.e. differences in external wall area etc). There will also be differences due to the different boilers used. And finally, we hope, differences due to the solar design.

In the previous chapter we have produced a fairly crude breakdown of the energy uses in the different house types, but we would like to know answers in more detail in order to make hard recommendations for future house design.

In the following sections we will present three different sorts of analysis and one synthesis, which all aim to improve the resolution of the project results, especially the solar ones.

A. Statistical Analysis

The first of these is a statistical analysis of annual total space heating consumptions, which aims to reduce the variation in the raw data by correcting for known differences between the houses. The three corrections applied are for differences in fabric loss due to levels of terracing, differences in mean internal temperatures, and differences in number of occupants. The correction factors themselves are derived from the data. Correction factors could have been worked out for the first two differences on a theoretical basis, but using the data itself seems more convincing.

The procedures succeed in improving the resolution of the results, but not sufficiently to produce any significant solar answers. An important discussion in this analysis involves the temperature correction of the data.

B. 'House Characterisation'

The second method, referred to as 'house characterisation', makes use of the fact that we have available weekly data on energy use. Since the temperature and solar radiation vary independantly from week to week the weekly data can be analysed to estimate the effect of each of these variables on the energy use. Making certain simplifying assumptions the energy balance of the house can be written as

$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

where	Q	is the auxiliary space heat
	K	is the sum of the incidental gains
	$\sum U.A$	is the house fabric specific loss
	C_v	is the ventilation specific loss
	ΔT	is the temperature difference (internal - external)
	R	is the effective solar aperture
	S	is the solar flux

This heat balance equation can be evaluated using statistical methods. Correlating Q against ΔT and S can produce estimates for K, $\sum U.A + C_v$, and R as unknowns. Alternatively, we can ignore the solar gains, concentrating on dull weeks only and using estimates for K from measured electricity use and cooking. By plotting Q+K against ΔT for dull weeks, we can estimate $\sum U.A + C_v$, as shown in figure 6.2.

Another procedure, used mainly in the Linford project, has been to plot $(Q+K)/\Delta T$ against $S/\Delta T$. As shown in figure 6.3 this plot gives estimates for both the total house heat loss $\sum U.A + C_v$ and the solar aperture or 'recuperation factor', R.

TOTAL ANNUAL GAS CONSUMPTIONS

October 1981 - September 1982

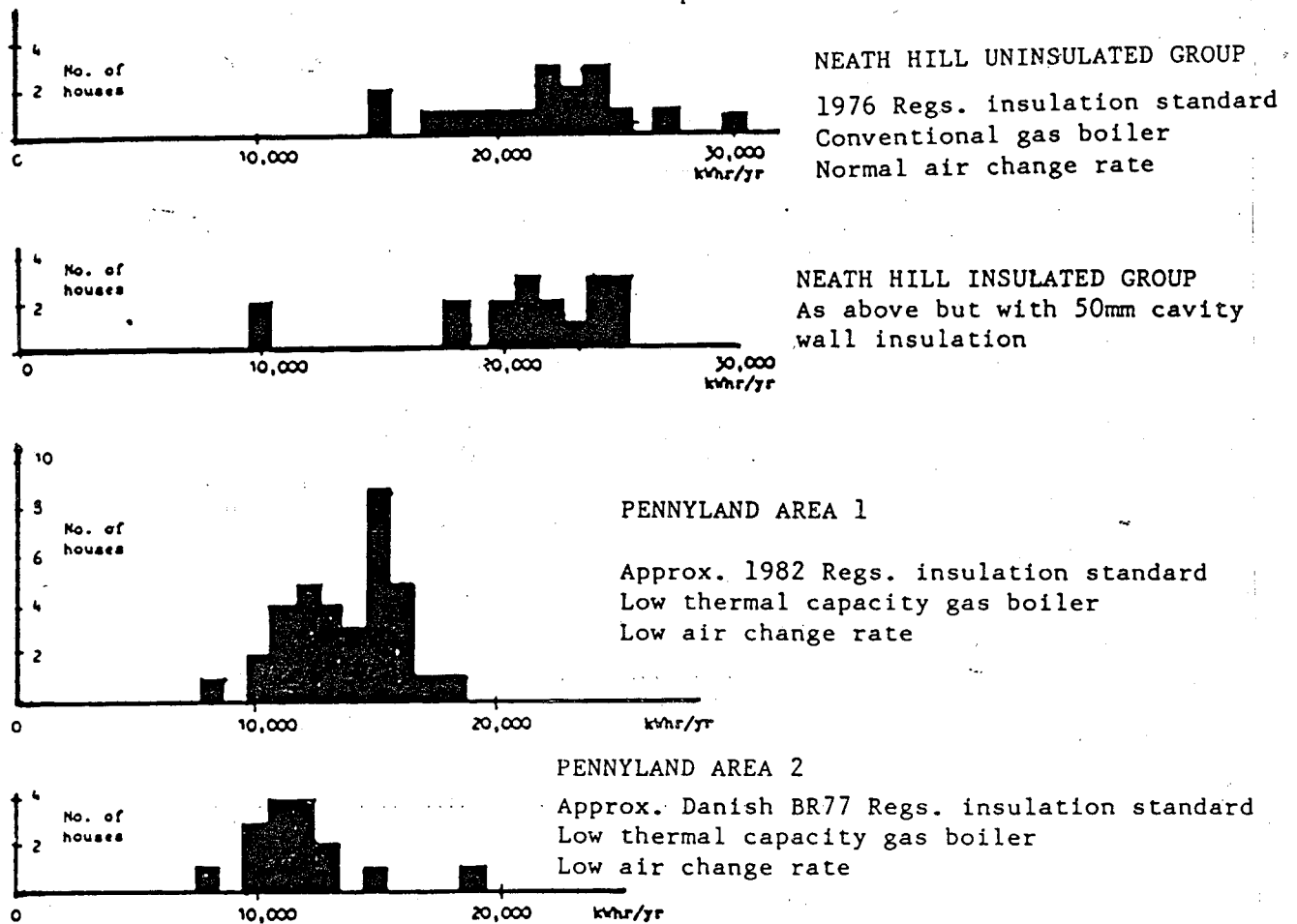


Figure 6.1 Annual gas consumptions for the four main insulation groups

'HOUSE CHARACTERISATION'

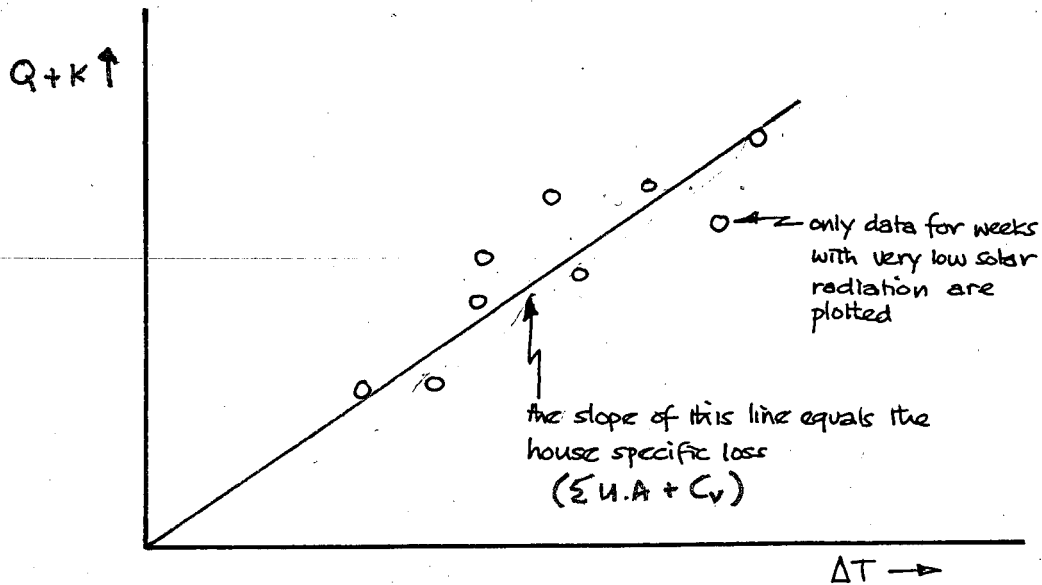


Figure 6.2 The plot of $(Q+K) \vee \Delta T$ can be used to estimate the house specific loss

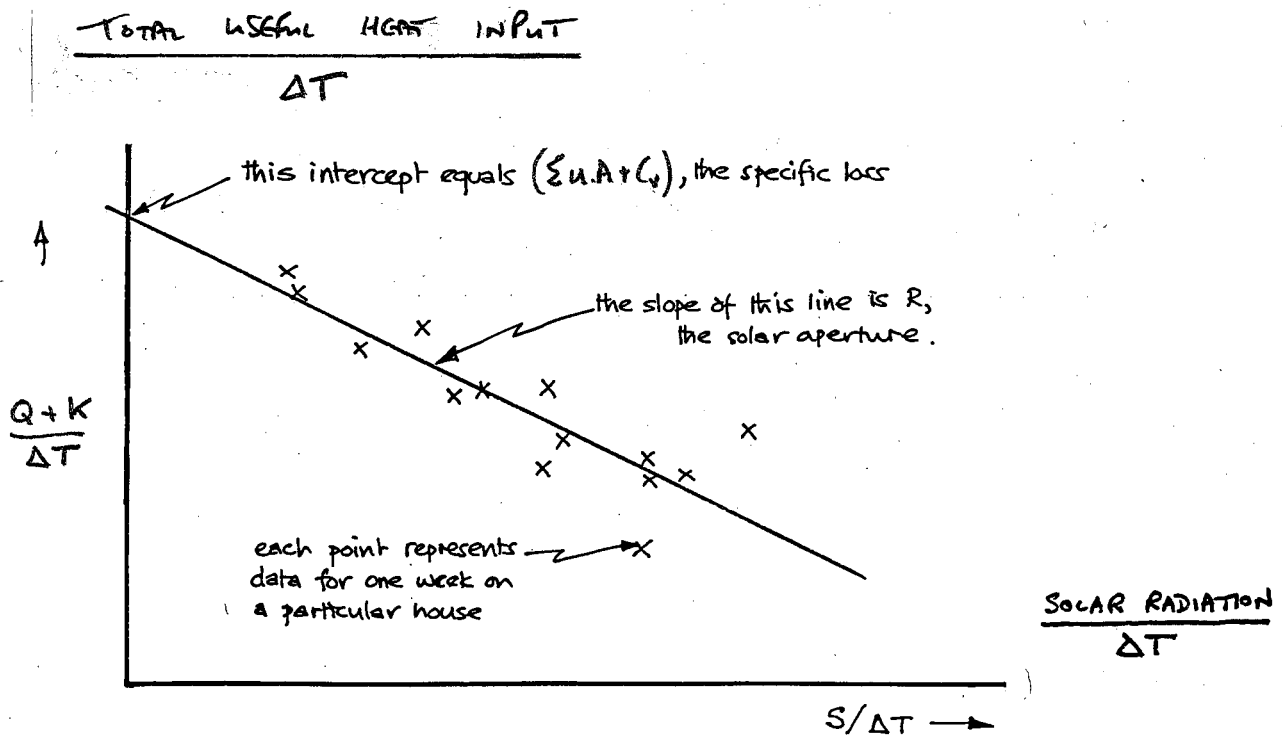


Figure 6.3 A plot of $(Q+K)/\Delta T \vee S/\Delta T$ provides estimates of both the solar aperture and the specific loss

C. Energy Balance Method

The third procedure used to analyse the data is the Energy Balance method. In this method a full energy balance for each house (or group of houses) is assembled from all the best data available. In order to compute this balance for each time period (the analysis is done weekly and combined into monthly and annual totals) extra assumptions have to be introduced about the terms which are not measured directly. The full balance is

$$\begin{array}{ccccccc} \text{incidental} & + & \text{solar} & + & \text{boiler} & = & \text{fabric} & + & \text{ventilation} & + & \text{DHW} & + & \text{flue} \\ \text{gains} & & \text{gains} & & \text{gas} & & \text{loss} & & \text{loss} & & \text{loss} & & \text{loss} \end{array}$$

The details of how the balances have been assembled are set out in Appendix 11. There have been two procedures used. The first estimates the solar gains from an assumed solar aperture and leaves the ventilation loss to be estimated as a residual in the balance. The second procedure estimates the ventilation loss from the pressure test data coupled to a simple model (described in Appendix 7). In this second balance the solar gains are left as the residual, and are thus estimated by a different route. The main problem with estimating either the ventilation loss or the solar gains by this method is that the errors in all the other terms are compounded into the estimate made.

This method is important, since it was the one suggested for use in a Europe-wide analysis of performance of passive solar houses as part of the C.E.C. Solar Energy Programme.

D. Extending the design modelling

The fourth method used was a 'synthesis' rather than an 'analysis'. By bringing together the experimental results of both the Linford and Pennyland projects and other new information, it has been possible to update the design computer model. This has then been used to estimate the energy consumptions of the various experimental house types and provide a detailed breakdown of the energy savings.

Although this method can produce very definite statements of savings not clouded by the statistical problems of the other methods, the credibility is very dependent on the mechanisms of the model itself and the degree to which it has been validated in various tests.

The detailed assumptions made in each method are discussed in the following sections. Although no individual method contains the 'whole answer', they all add up to provide a picture of the energy use in the houses and the magnitudes of the energy savings that have been made.

6.2. Statistical analysis of annual space heating

All the analyses presented in this section start with the best estimates of the useful space heating energy, derived by the processes explained in section 5.5. This means that use has already been made of the data collected and evaluated on the boiler efficiencies and gas used for water heating. For all the reasons set out in Section 5.5 this derived data is regarded as being the most accurate and useful data set on which to base the analyses.

First we shall discuss the statistical significance of these results, then we shall consider techniques for reducing the variation.

In order to illustrate the nature of the problem it is instructive to look at the best estimates that can be made of the savings from the data derived in section 5.5.

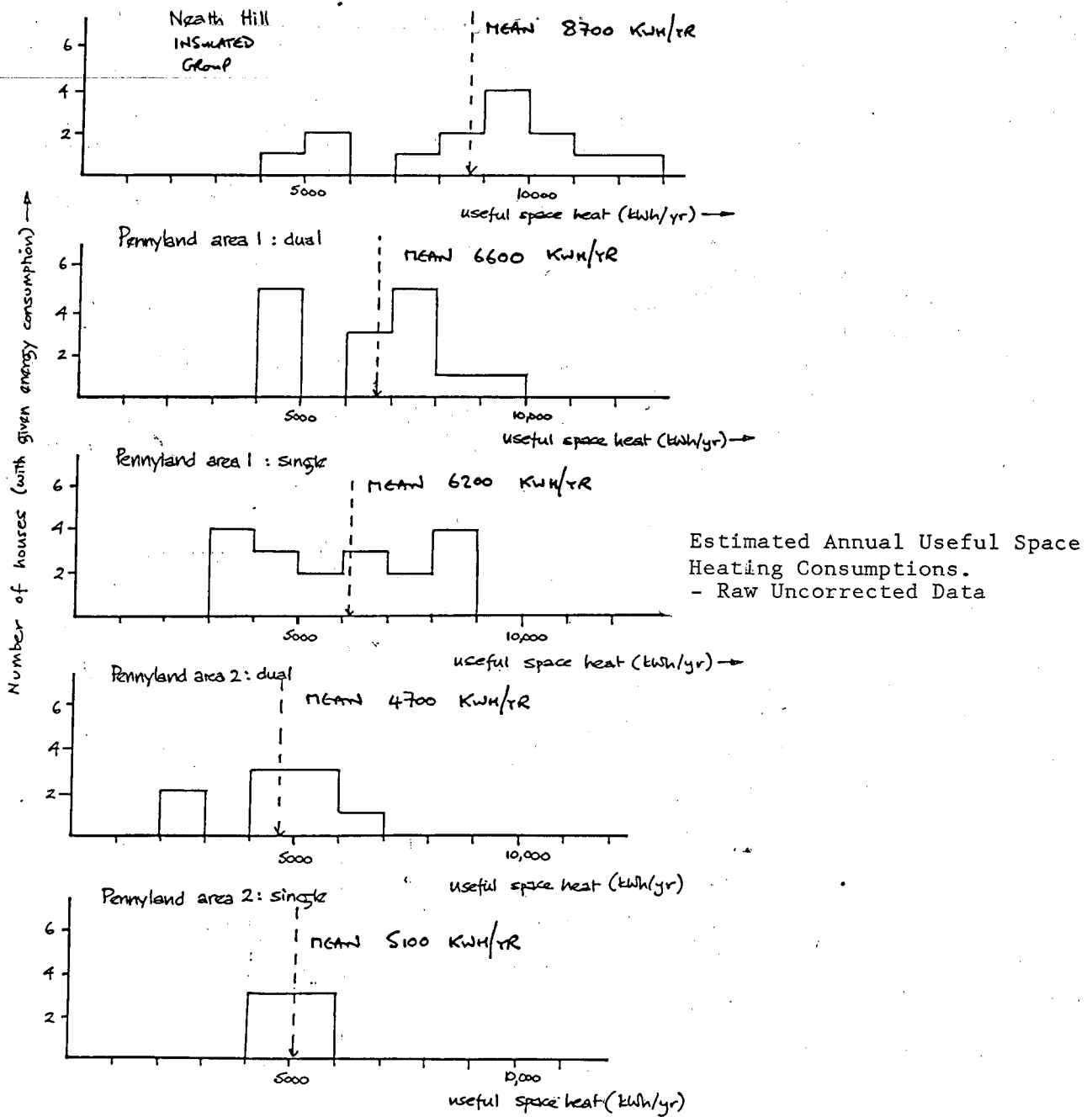
Histograms of the results of these computations for the 5-person houses for which there are good data sets are shown in Figure 6.4. The corresponding average values and savings are set out in Table 6.1. Also shown in the table are the "standard errors" associated with the data. These standard errors are based on the distribution of observed energy consumptions for each house type, they are NOT estimates of measurement errors. This standard error is the experimental equivalent of the standard deviation discussed in Section 2.3 and can be used, in conjunction with standard statistical tables, to estimate the confidence associated with an observation. As explained in section 2.3 (and Appendix 2) the confidence also depends upon the number of houses in the sample.

Table 6.1 Raw energy data and estimates of savings

House type	Useful space heat (kWh/yr)	Average energy savings		
		cf Neath H.	cf Penny. 1	Solar
Neath Hill	8700±590			
Pennyland 1	6400±420	2300±720		
Pennyland 2	4900±310	3800±700	1500±560	
Pennyland 1 dual aspect	6600±400			
single aspect	6200±450			450±600
Pennyland 2 dual aspect	4700±490			
single aspect	5100±200			-400±530

(Note: differences derived before rounding)

Figure 6.4



These results will be discussed in further detail below, but for now the point to note is that the insulation savings seem quite clear, that is the magnitude of the saving is several times the standard error. This is in fact a major result and appears to be the first time that a UK field trial has produced such clear evidence of energy savings from insulation.

There is one result which has not yet been presented, namely the comparison between the uninsulated and insulated groups on Neath Hill. This is not a happy comparison because the only data available on the uninsulated group is from quarterly gas bills, and as has been demonstrated these can obscure crucial detail. For the data to be compatible we compare the gross gas consumption of the two groups of houses. For the uninsulated group the gas consumption is 23400 kWh/yr, for the insulated group it is 20900 kWh/yr. The difference is 2500 kWh/yr with a standard error of 1700 kWh/yr.

This result is the product of an attempt to compare a selection of houses, like-with-like, and consequently does not agree with the figures shown in Chapter 1, which is for a larger sample of houses. The fact that the answer can change with the sample chosen simply illustrates the statistical problem.

The Statistical significance of the Raw results

The statistical t-test has been used to assess the statistical significance of the results. It is found that the difference between the Pennyland 1 and Pennyland 2 is significant at the 99% level; in other words such a difference would only occur by chance in 1 out of 100 cases.

This clearly indicates that there is some reduction in energy consumption associated with the increased insulation.

However the 95% confidence interval for this energy saving is roughly 300 to 2700 kWh/a. This is a very wide range - the fact that we are 99% certain that there is actually an energy saving does not mean that we know precisely what that saving is. This uncertainty is important, for example for economic analysis. Put simply, our 95% confidence interval would imply a 9 to 1 range of possible pay back times for the technical measures introduced at Pennyland 2. To be certain that these measures are worthwhile we need to try to narrow this range down.

An even clearer result is the energy saving of Pennyland 2 over Neath Hill. The probability that there is an energy saving here is better than 99.9%, and the 95% confidence interval for the saving is roughly 2300 to

5300 kWh/a. Bear in mind that this difference excludes differences due to the heating system - it is an estimate of the effect of the changes in the building fabric and estate layout only. Having said that this result is clearer than the insulation saving at Pennyland, it must be said that the question is less clear. There are so many differences between Pennyland and Neath that the contribution of any one of them to the overall saving is no more certain than the insulation saving at Pennyland.

Finally the marginal passive solar savings at Pennyland are very uncertain. The 95% confidence intervals at Pennyland 1 and 2 are about -1000 to +2000 kWh/a and -2000 to +1000 kWh/a respectively. This is too wide a range to be particularly useful.

Within-group corrections

It is known that the useful space heating of a house will depend upon the fabric loss and the mean internal temperature over the heating season. There will also be some dependence on the number of people in the house since this will affect the sum of the incidental gains. It is also known that these factors vary widely from one house to another. The first step in reducing the variation in the energy consumptions is therefore to develop a procedure for correcting for these differences within any one group of houses. The range of fabric losses and heating season mean temperatures are illustrated, for Pennyland 1 dual aspect houses, in Figure 6.5.

The procedure which was used to make this correction was to use the data itself to estimate the coefficients which relate energy consumption to these variables. Different combinations of variables were tried and it was found that the variance was reduced most by using the product of fabric loss and temperature difference plus occupancy. The coefficients were estimated by a least squares fit to an equation of the form

$$Q = a (F \Delta T) + b P + c$$

where

a, b and c are coefficients

Q is the useful space heat

F is the fabric loss

ΔT is the heating season average temperature difference

P is the number of people

* It seems that in our area of endeavour one can either have clear answers to rather woolly questions, or woolly answers to clear questions, but rarely clear answers to clear questions.

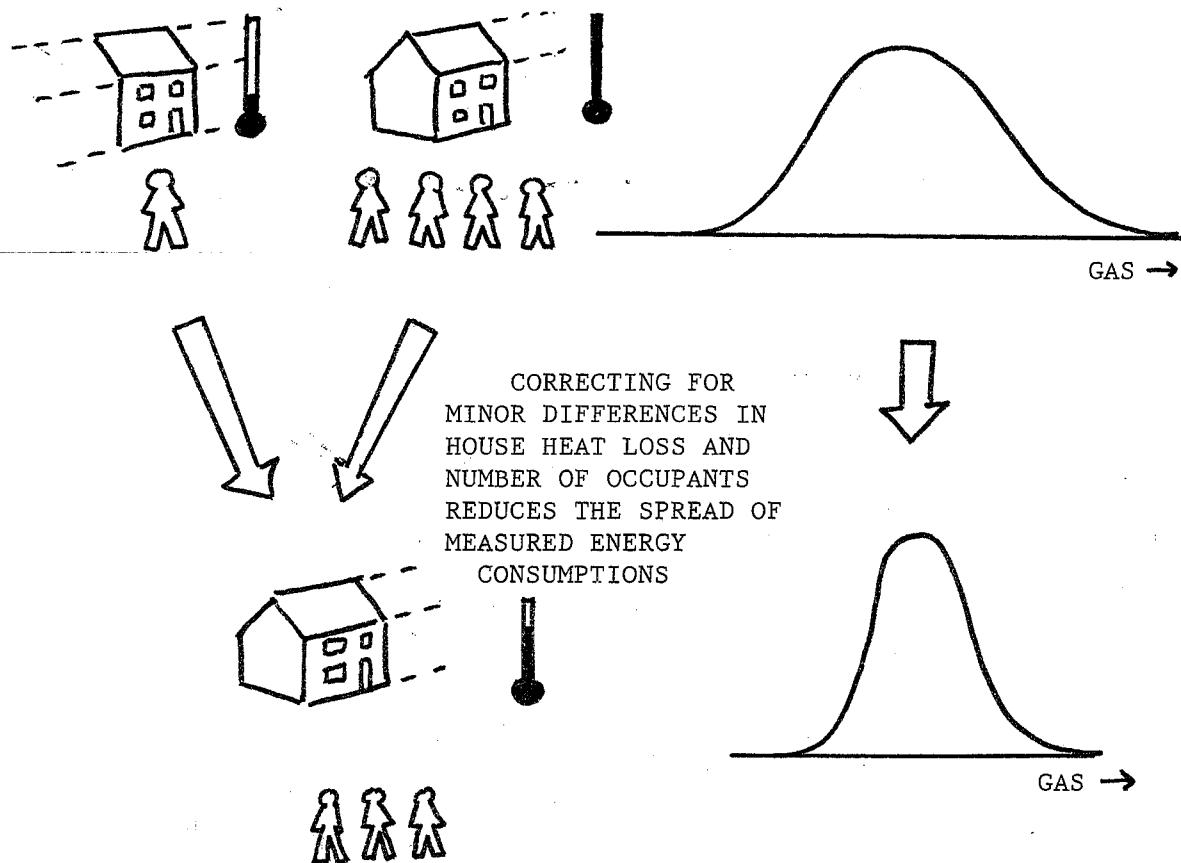
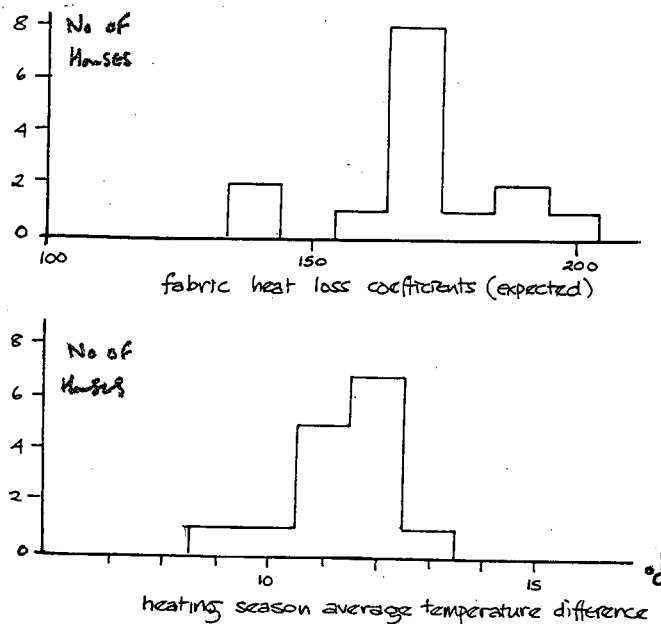


FIGURE 6.5

VARIATION OF HOUSE
FABRIC HEAT LOSS
AND INTERNAL
TEMPERATURE IN
PENNYLAND AREA 1



Initially individual house groups were tried in the regression equation, but the coefficients produced were not particularly statistically significant. The effect of the number of occupants, in particular, was very weak. It seemed to be positive (i.e. increasing space heating use with number of occupants) except in one group, the Pennyland 1 dual aspect houses, where it was negative (i.e. more occupants use less space heating energy).

Similar results were noted in relating water heating consumption with number of occupants and it is possible that the space heating effect is either due to genuine interactions between hot water consumption and space heating demand by way of free heat gains, or due to imperfections in the process of separating water heating from total gas consumption as described in section 5.6.

For the purposes of correcting the distributions in this chapter a pooled estimate of the $F\Delta T$ coefficient has been used from all the groups, but separate occupant coefficients were used for the Pennyland 1 dual aspect house groups and all the others, viz:-

Weighted $F\Delta T$ coefficient	=	0.39 ± 0.05
Occupancy coeff. for PlDA	=	-89 ± 13 W/person = -800 ± 120 kWh/yr/person
Occupancy coeff. for rest	=	57 ± 22 W/person = $+600 \pm 200$ kWh/yr/person

There is little that we can say about the likely values for these coefficients. We would expect a value of about 0.5-0.6 for the $F\Delta T$ coefficient. This is simply the fraction of the year occupied by the heating season (i.e. Oct-Apr.). The value of 0.39 is reasonable given the tendency of least squares regression procedures to underestimate coefficients given a less than perfect fit.

It is easy to think of reasons why the occupancy coefficient should be either positive or negative. Why it should be both is simply a mystery. Fortunately, the occupancy correction has not been very important in the group comparisons.

Using these coefficients the energy consumption for each house could be corrected to the average internal temperature for the group and to the fabric loss associated with an end of terrace house in that group. All the consumptions were also adjusted to three occupants per house.

The resulting histograms are shown in Figure 6.6. As hoped the variance has significantly reduced. It is now also noticeable that the distributions of energy use appear more gaussian (i.e. closer to a bell shaped ideal distribution). The corrected estimates of the useful space heating, and the corresponding savings, are set out in Table 6.2.

Table 6.2 Corrected energy data and estimates of savings

House type	Useful space heat (kWh/yr)	Average energy savings		
		cf Neath H.	cf Penny. 1	dual-single
Neath Hill	8800±360			
Pennyland 1	6500±330	2300±490		
Pennyland 2	5100±310	3700±420	1400±400	
Pennyland 1 dual aspect single aspect	6500±330 6600±320			-130±460
Pennyland 2 dual aspect single aspect	5100±310 5200±80			-50±310

(Note: differences derived before rounding)

As might be expected, the biggest effect of making these corrections is on the uncertainty in the energy savings. The energy consumptions and savings themselves do not move very much. We are now more than 99.9% certain that the application of the Pennyland 2 insulation measures would result in an energy saving compared to houses built to the Pennyland 1 level. Perhaps more importantly, the 95% confidence interval of this saving is now roughly 540 to 2300 kWh/a. Although this is still a 5 to 1 range, it is an improvement on 9 to 1 for the raw estimates, and moreover the lower limit has risen by nearly a factor of 2. Less stringently, we are 90% certain that this saving is bigger than about 860 kWh/a.

The 95% confidence interval for the saving due to the application of the Pennyland 1 measures compared with Neath Hill is about 1200 to 3400 kWh/yr.

Raw space heating
estimates from figure 6.4

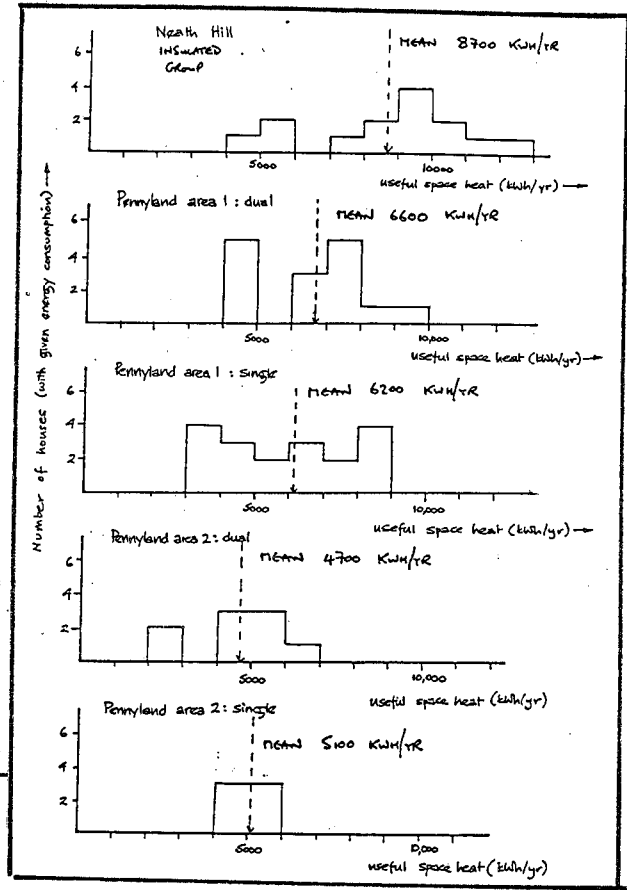
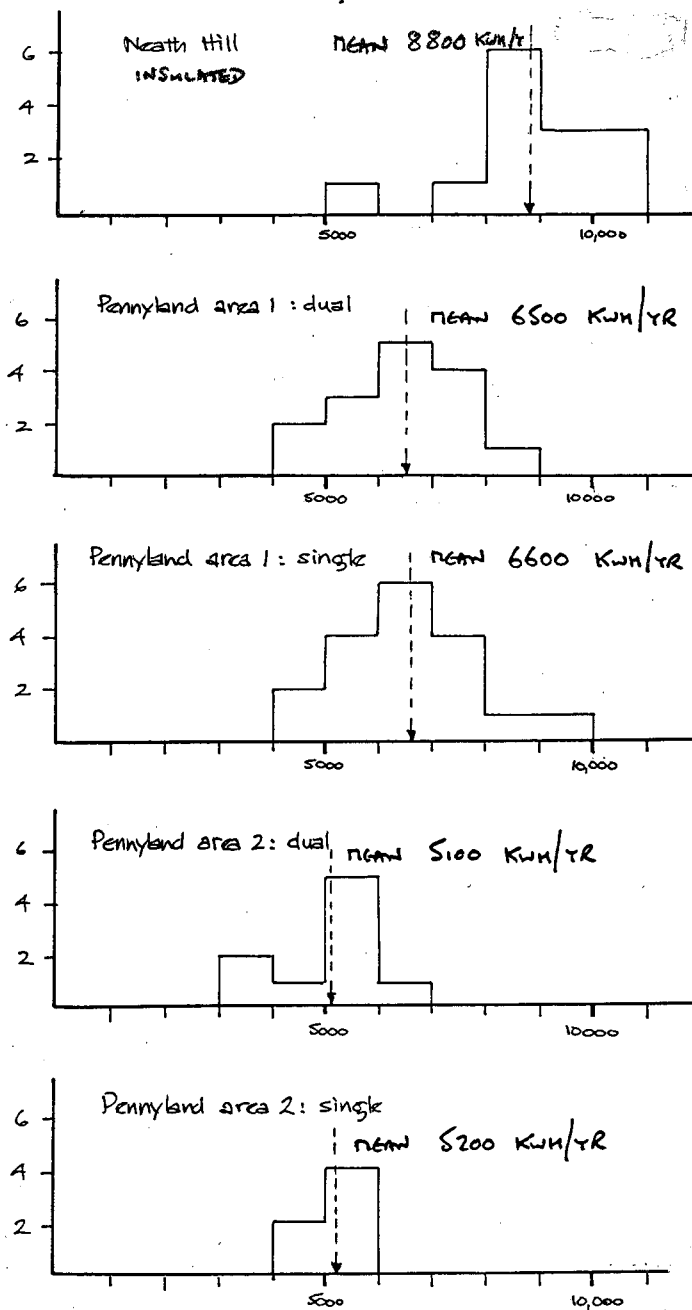


Figure 6.6

Correcting for
within-group
variations in
fabric loss and
internal temperature
reduces variance
by about 30%.

Again the solar savings, are not significant. The 95% confidence intervals are about ± 1000 in both area 1 and area 2 houses. This is what we expected, though obviously narrower confidence intervals would be desirable.

Between-group corrections

Although the above procedure has reduced the variation within each group there remain a number of significant differences between the groups of houses that have not yet been corrected. By using the calculated estimates of useful space heating the differences in boilers between Neath Hill and Pennyland has already been taken into account. However an examination of the average values of the fabric losses, internal temperatures and occupancy shows that there remain important differences in the last two variables (obviously differences in the fabric loss are not to be eliminated - they are differences we wish to examine!) The values are set out in Table 6.3

Table 6.3 Average values of fabric loss, heating season temperature differences and number of occupants.

House type	Sample size	Fabric losses end terrace	average terrace	Temperature difference (htg season)	Occupants (number)
Neath Hill	14	171	165	13.5	3.3
Pennyland 1 dual aspect	15	171	172	11.4	3.2
single aspect	18	193	180	12.8	3.2
Pennyland 2 dual aspect	9	115	108	12.4	2.8
single aspect	6	129	124	14.0	2.8

The dominant difference between the groups of houses is in the temperature. There is a 1°C difference between insulation levels and 1.5°C difference between dual and single aspect houses. Obviously these temperature differences will affect the energy consumption, as discussed in section 5.6.1 and illustrated in Figure 6.7. In Figure 6.7 the top curve represents the variation in energy with temperature for a Pennyland area 1 type house, the bottom curve shows the same for a Pennyland area 2 type house. The average temperature on Pennyland area 1 is shown as P1, P2 shows the average temperature for Pennyland area 2 houses. The

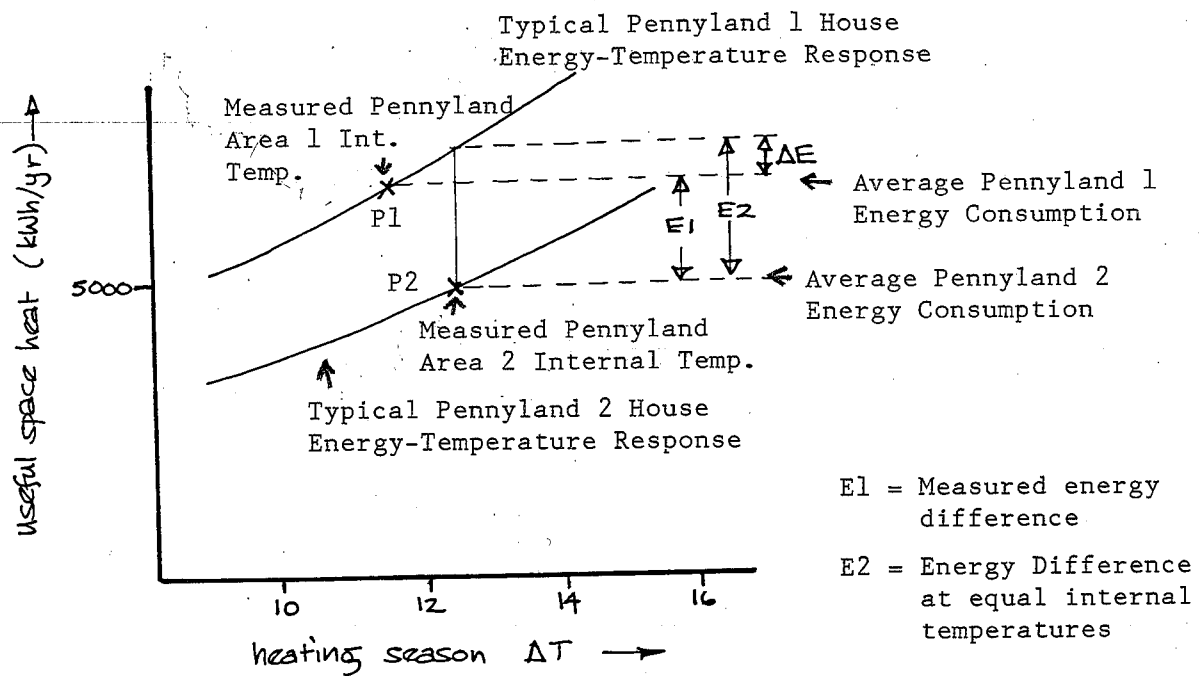


Figure 6.7 Illustrating the relationship between average heating season temperature differences and useful space heat savings

observed difference in space heating energy is E_1 . The energy that would have been saved had both groups of houses had the same temperature is shown as E_2 . In this example the difference between these two estimates of the saving is 600 kWh/yr.

The difficulty that we face is that we are not simply trying to account for physical energy flows and temperatures, but to guess how valuable these are to people. We have no way of knowing whether the occupants of Pennyland 2 and the single aspect houses value these temperature bonuses (which occur mainly in the bedrooms) as much as the energy savings which have been forgone to obtain them. If the temperature bonus is as valuable to people as the lost energy saving $\Delta E'$ then it is useful to estimate the energy saving that would have occurred if both groups had had the same mean temperatures. (Perhaps this should be called the isothermal energy saving?) If the value of the temperature bonus is zero then the most useful indicator of the energy saving is the raw energy saving. The area is complex (see for example ref. 6.1). We will estimate both the energy savings with and without the energy saving value of the temperature differences between the groups of houses, and leave the reader to decide which is the most appropriate to use for themselves.

The discussion of the effects of temperature differences between the groups has been quite long. This was necessary because temperature is not independent of insulation level or solar design. The two other between-group variations that we mentioned earlier (number of occupants and terracing level) are independent of insulation and solar design, and we therefore feel justified in attempting to correct the auxiliary energy consumptions for these differences.

Figure 6.8 shows the effect of correcting the space heating energy used to a common heating season average internal temperature 18°C . The corrections were carried out using the same coefficients as for the within group corrections. The main effect is to increase the difference between the Pennyland insulation levels, to reduce the difference between Pennyland and Neath Hill and to increase the energy savings of the single aspect houses at Pennyland compared with the dual aspect houses. The first of these is what would be expected - insulating houses

There may be some subtle connections between the layout of an estate of single aspect houses compared with one of dual aspect houses which could introduce a connection between passive solar variant and terracing, but this is beyond the scope of this report. The observed correlation between insulation level and number of occupants at Pennyland and Neath Hill is probably due to the fact that the better insulated houses were occupied later, and their occupants have therefore had less time to raise families.

Within-group corrected data
from figure 6.6

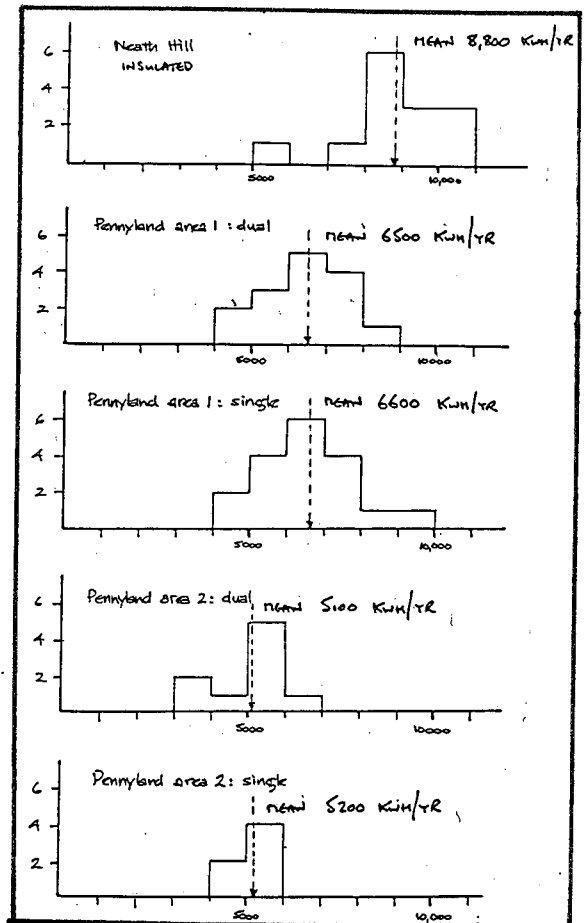
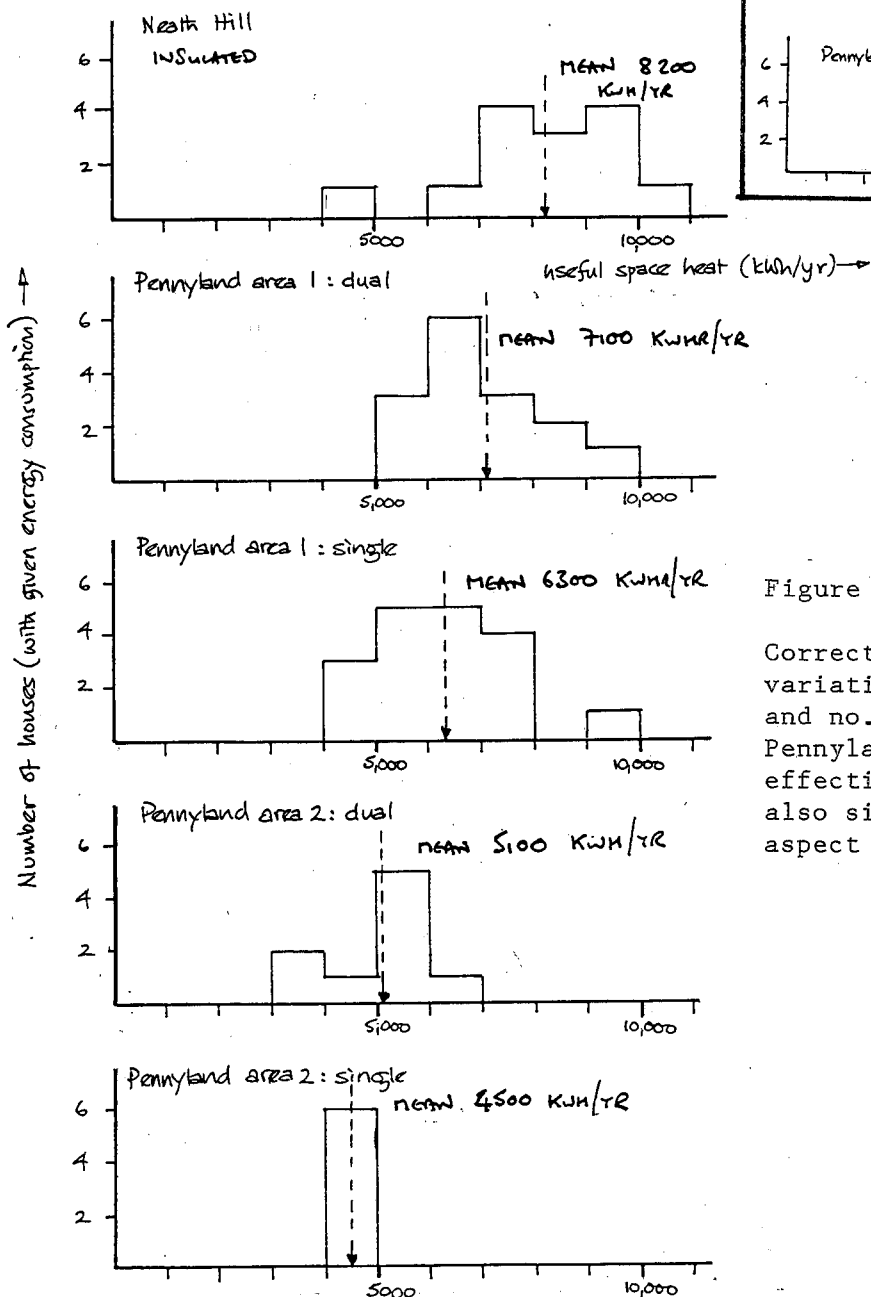


Figure 6.8

Correcting for between-group variations in internal temp. and no. of occupants increases Pennyland 1 - Pennyland 2 effective energy savings and also single aspect - dual aspect difference.

tends to result in higher temperatures, particularly in houses which do not have full central heating systems, and where the heating system is used intermittently. Correcting for such temperature rises increases apparent savings. The second is not really what we would expect, but we know of several possible reasons for the difference in temperatures between Pennyland 1 and Neath Hill - higher infiltration rates at Neath Hill, differences in room layout, and not least the fact that some of the Neath Hill houses have full central heating systems. The effects of the solarisation of the Pennyland single aspect houses is qualitatively what would be expected, but for two reasons the temperature differences between the dual and single aspect houses may be exaggerated - the first is the problem of the siting of the external temperature probes in the dual aspect houses on Pennyland 1, and the second is the fact that the temperature probes upstairs are in south facing bedrooms. The new average energy consumptions and savings are as set out in Table 6.4

Table 6.4 Corrected energy data and estimates of savings
(corrected to same average internal temperature)

House type	Useful space heat (kWh/yr)	Average energy savings		
		cf Neath H.	cf Penny. 1	dual-single
Neath Hill Insulated	8200±360			
Pennyland 1	6700±330	1500±490		
Pennyland 2	4800±270	3400±420	1900±400	
Pennyland 1 dual aspect	7100±330			
single aspect	6300±320			750 ±460
Pennyland 2 dual aspect	5100±310			
single aspect	4500±80			630 ±310

(Note: differences derived before rounding)

The 95% confidence interval for the Pennyland 2 insulation measures compared with the Pennyland 1 level of insulation is now about 1000 to 2800 kWh/a. The width of the interval is the same as before when we were not counting the temperature difference between Pennyland 1 and 2 as an additional energy saving, but the ratio of the upper to the lower confidence limit is now only (!) 2.8 to 1.

On the basis of these figures, we are more than 99.9% sure that the results of this insulation step are equivalent to an energy saving, and we are 90% certain that the value of the saving is greater than about 1300 kWh/a.

The 95% confidence interval for the saving due to the application of the Pennyland 1 measures compared with Neath Hill is about 400 to 2600 kWh/a. On this basis the widespread application of Pennyland 1 construction techniques (assuming we have accurately identified the ones that make the difference!) has a 99% probability of giving an energy saving compared with Neath Hill type houses.

Counting temperature rises as equivalent to energy savings leads to quite a dramatic shift in the confidence intervals for the solar savings. There is now about a 90% probability that widespread application of the Pennyland single aspect as opposed to the dual aspect passive design would save energy or produce equivalent temperature increases. This result has to be quite heavily qualified however. The fact that the upstairs temperature was only sampled in south facing bedrooms will overestimate any effects of increasing the south facing window area of the house. Also the fact that outside temperature was measured on the north side of most of the Pennyland 1 dual aspect houses will tend to lead to overestimates of the effect of passive design on temperatures in these houses.

Conclusions from Statistical Analysis

A number of important conclusions can be drawn from the above analyses. These are summarised, in terms of the useful energy savings (except where stated), as follows.

Although the Neath Hill estate has failed to act as a control for the passive solar part of the experiment, the comparison between Pennyland and Neath Hill has demonstrated a number of significant energy savings.

1. There is a saving of about 3400 kWh/yr of gas due to the different boiler used on Pennyland. Whilst it is difficult to estimate the uncertainty in this figure it is certainly no more than ± 500 kWh/yr. This result is important since it is the largest single energy saving demonstrated in this project.
2. There is an additional difference of about 2000 kWh/yr in the useful space heating between Neath Hill and Pennyland 1. This can be attributed to some combination of differences in infiltration rates and solar gains. The raw difference is 2300 kWh/yr which remains the

same after correction for within-group differences in temperature and fabric heat loss. Adjusting the figure to a common temperature reduces the difference to 1500 kWh/yr. This is the same as the estimate made of the difference in ventilation loss (see section 4.6), though the large assumptions made do give this wide error margins. Given the large differences in boiler efficiency as well, it is impossible to say whether there is a solar difference (of the order of 500 kWh/yr) or not.

3. There is a highly statistically significant saving between areas 1 and 2 of the Pennyland estate. Perhaps the most cautious estimate is 1400 ± 400 kWh/yr. This would imply a minimum saving at 90% confidence of 860 kWh/yr. This estimate takes into account differences in terracing and within group temperature differences, but not the overall temperature difference between the two halves of the estate.

Allowing for this apparent internal temperature increase in Area 2 as an equivalent energy saving increases the saving estimate to 1900 ± 400 kWh/yr of useful space heating energy. This implies a minimum saving at 90% confidence of 1300 kWh/yr.

4. On the basis of both raw data and data corrected for within-group temperature variations, there is not any detectable difference in energy consumption between the single and dual aspect house designs.

There is, however, an apparent increase in internal temperature in the single aspect design, though some of this may be a monitoring artifact. If the increase in temperature between the two house types is taken as real and useful, there is a detected energy saving of approximately 700 ± 400 kWh/yr. This is significant at a 90% level.

6.3 House Characterisation

As outlined earlier, the weekly measured data can be analysed by statistical means to build up an energy balance of the form:-

$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

where

- Q = Weekly measured space heating
- K = Weekly free heat gains from cooking, lights, etc.
- $\sum U.A$ = House fabric heat loss
- C_v = House ventilation heat loss, assumed constant
- ΔT = Weekly average inside-outside temperature difference
- R = Equivalent clear 'solar aperture'
- S = Weekly total solar radiation on south-facing vertical surface

This statistical analysis can be done in several different ways:-

1. The 'triaxial' or 3-dimensional method. treating K, $\sum U.A + C_v$ & R as unknowns.
2. The 'low solar' method using only dull weeks when the solar gains can be ignored and assuming K to be known, to determine $\sum U.A + C_v$.
3. Siviour's two-dimensional method, assuming K to be known and determining $\sum U.A + C_v$ and R.

All of these methods have been used on the data with varying degrees of success. The last method has been used extensively on the Linford data to determine both the solar aperture and the house fabric heat loss under different conditions.

Linford test house results have shown that for really consistent answers it is necessary to measure both the floor heat loss and the continuously varying ventilation loss separately. The reason for measuring the floor loss independently is that solid floors of the type used at Pennyland and Linford respond more to a slowly changing soil temperature than external air temperature. The floor heat loss thus does not respond to the same ΔT as the walls or the roof.

Having produced good answers for the Linford test house, these showed good agreement with measurements in the adjacent occupied houses, although a large number of assumptions have been necessary.

A full description of the methods will be found in the Linford project report and also, with a discussion of the Pennyland results, in the companion Thermal Calibration report.

6.3.1 Solar Aperture

First a little explanation is required about the way in which the solar gains into a house have been treated.

It is assumed in the Pennyland and Linford projects that useful solar gains into a house are proportional on a daily or weekly basis to the measured solar radiation on the south-facing vertical surface, recorded outside the house and at 10 metres height (thus making it free from overshadowing problems). These measurements make no effort to exclude ground reflected radiation.

While this is not a perfect choice of solar variable, it is a good compromise between one that is a linear function of solar gains into a south-facing Pennyland/Linford type house and a 'meteorological' weather variable. South-facing solar radiation (excluding ground-reflected radiation) is measured at Bracknell and Lerwick and this data can thus be used to extrapolate results to other U.K. sites and years.

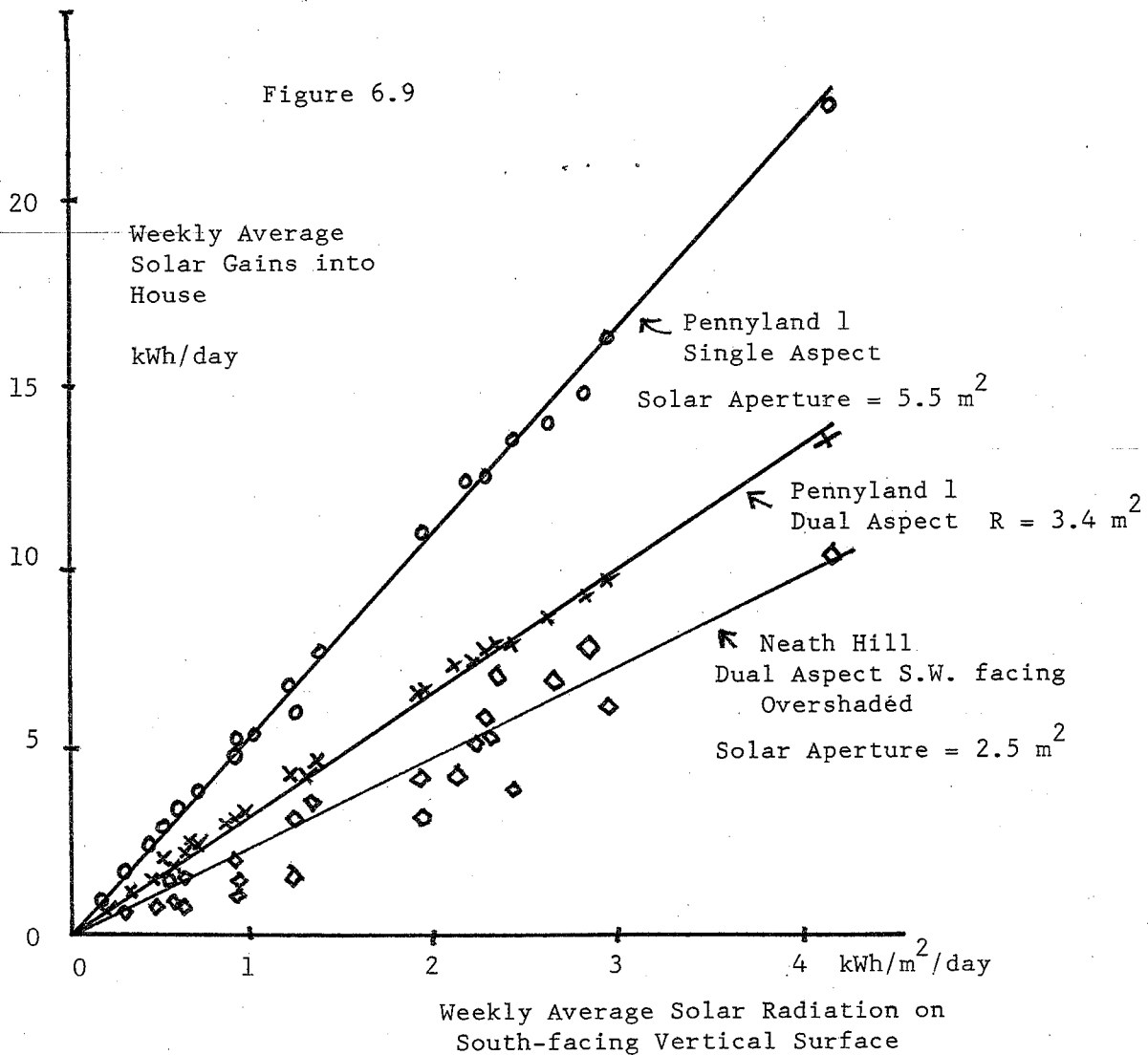
Previous projects and calculation systems have used solar radiation on the horizontal surface as the primary solar variable, with the result that solar gains into the house are a distinctly non-linear relation (see refs. 6.2 & 6.3).

The coefficient of proportionality of solar gains into the house to the south-facing vertical solar radiation is taken as being equivalent to a clear south-facing solar aperture. It must be stressed that this is purely a mathematical quantity, including as it does, gains on the north-facing side of the house and through the opaque brickwork, as well as the effects of overshading and window absorptivity. It is not directly related to the south-facing window area.

It has been given the symbol R since it is very similar in function to the solar 'recuperation coefficient' of the 'temperature without heating' calculation method developed at Liege (ref. 6.4).

Figure 6.9 shows computed solar gains into a Pennyland dual aspect house, a single aspect house, and a Neath Hill type dual aspect house, with overshading and facing south-west. This shows that the concept of a solar aperture with respect to south-facing solar radiation on the vertical surface is reasonable for the Pennyland houses but only roughly so for the Neath Hill ones.

It should be stressed that by 'useful' solar gains into a house we mean those that can be used either for increasing internal temperature or reducing space heating. Whether or not these solar gains are turned into a reduction in space heating requirement depends on many factors which cannot simply be determined (heating system control response, whether there is a space heating demand to be supplanted, etc.)



Solar gains into house as a function of south-facing vertical solar radiation.

Both quantities have been computed on an hourly basis, taking into account the transmission properties of windows and with an allowance for the reduced absorption due to net curtains derived from Linford measurements.

6.3.2. Triaxial Regression

Taking the heat balance equation

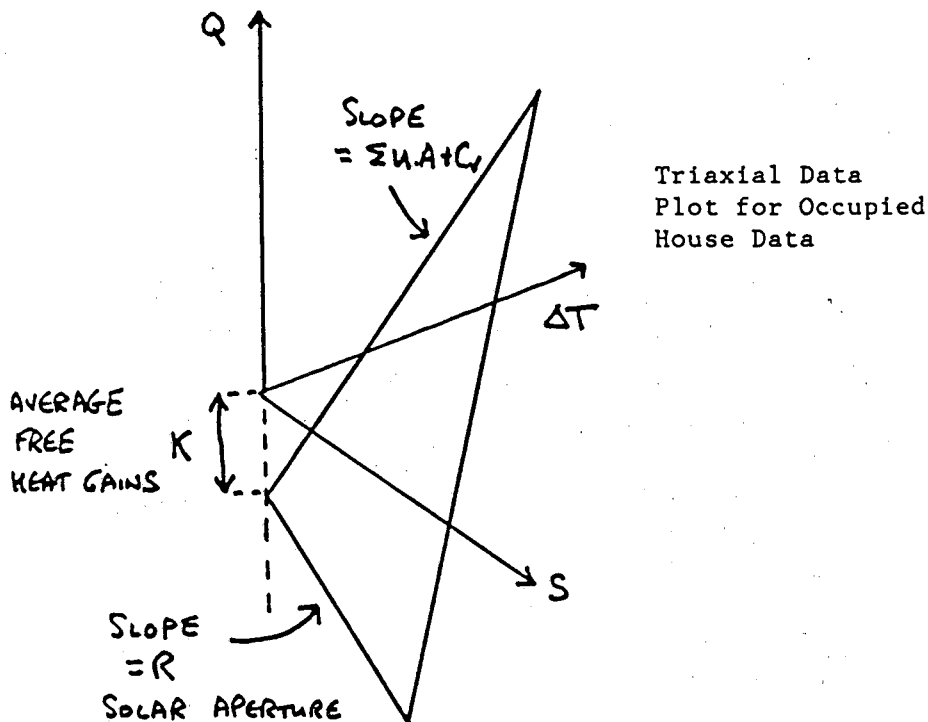
$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

and correlating Q with ΔT and S , it is possible to extract the three unknowns K , $\sum U.A + C_v$ and R .

This is equivalent to fitting a plane surface through data points lying in three-dimensional space between Q , ΔT and S axes.

Figure 6. 10

$$Q = (\sum U.A + C_v) \cdot \Delta T - K - R.S$$

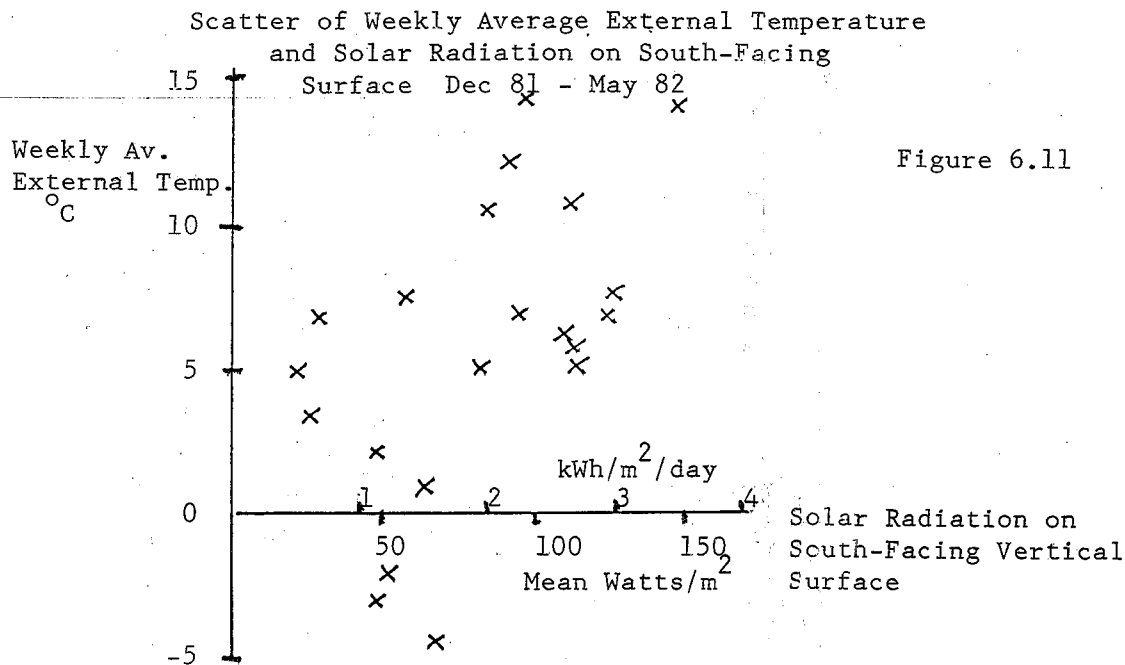


The slope of the intersection of this plane with that of the Q and ΔT axes should give the total house heat loss term $\sum A.U' + C_v$ and that with the Q and S axes should give the solar aperture R .

In practice, in assessing the performance of the house, we are at the mercy of available winter weather conditions to fix the various data points. As such, fitting a practical plane to them is not so easy.

In order to get a good fit to a plane we obviously need weeks with large values of ΔT and some with low values. We also need both sunny weeks and dull weeks. It is also vital that the two are not related, i.e. that the warm weeks are not all the sunny ones and that the dull

ones are not all cold. Fortunately the winter of 1981/82 has been obliging in producing a good mixture of weather. Figure 6.11 shows a scatterplot of weekly average outside air temperature and weekly average solar radiation from December 1981 to May 1982. This shows a good range of almost 20°C for the weekly average external air temperature and a reasonable range of weekly average solar radiation:-



The weather may not always be so suitable. An attempt to analyse the Linford test house data in this manner using ten weeks data from March to May 1982 was a miserable failure since the weather was just the same, week after week.

It is also vital to use 'clean' data for this kind of analysis, since least-squares regression is very sensitive to 'outliers' or odd points. For the two-dimensional methods these outliers can easily be seen when plotting the data, but when the data is in three dimensions, life is a little difficult. Various methods were tried to display the data, including 3-D computer graphics, ping-pong balls on string and plasticene on bits of wire, but all without much success. In practice outliers have been removed from the Pennyland data by using the 'large residual' detection procedure of the regression package itself. This is fine for the mathematics, but conveys little understanding of what is actually going on in the house.

The whole range of problems associated with this type of analysis are discussed in the companion Thermal Calibration report and research is still (June 1985) continuing on the topic.

Despite some doubts over the value of the method, it has managed to produce values of solar apertures for the various house designs that are in line with expected values, given the results from Linford.

Data has been pooled for each house type to give an 'average' house performance:-

Table 6.5 Estimates of solar apertures by weekly regressions

House group	aperture (sq.m)	sample size	theoretical value
Neath Hill	3.0±1.2	8	approx. 2.5
Pennyland 1	5.5±1.0	18	
Pennyland 2	4.1±0.7	7	
Pennyland 1			
dual aspect	3.7±0.9	9	
single aspect	7.3±1.7	9	
Pennyland 2			
dual aspect	5.0±0.8	3	
single aspect	3.4±0.9	4	
Pennyland 1&2			
dual aspect	4.0±0.7	12	3.4
single aspect	6.1±1.3	13	5.5

None of these answers is particularly statistically significant. The best estimate of the solar apertures for the single and dual aspect houses is given by pooling data from both Pennyland 1 and 2, giving effectively solar apertures of 4 m^2 for a dual aspect house and 6 m^2 for a single aspect one. These figures are comparable to values of 8 m^2 for the Linford test house with net curtains and 10 m^2 with no window clutter.

The values for the single and dual aspect houses also agree fairly well with those calculated by the computer model, in the light of the Linford results (see figure 6.9).

The regression values, including the 3 m^2 for the Neath Hill houses have been used to calculate solar gains in the 'fixed solar aperture' energy balances for the different house types.

These differences in solar aperture can be approximately be converted into differences in absolute solar contributions by multiplying by the total solar radiation incident over the heating season. This amounts to about $250 \text{ kWh/m}^2/\text{yr}$ on the south-facing vertical surface but is very dependent on the precise length of the heating season (see Linford report).

Thus the difference of about 1 m^2 in solar aperture between the Neath Hill houses and the Pennyland single aspect houses, corresponding to about 250 kWh/yr of heating energy, may be taken to be due to the correct orientation and avoidance of overshadowing, plus a slight rearrangement of glazing.

This figure is very similar to the value calculated by the NBSLD in section 6.5. Although it is at a very low level of statistical significance, this is the only measured indication from this project that the Pennyland dual aspect houses absorb more solar radiation than the Neath Hill control houses, other comparisons being clouded by the other differences between the house types (air infiltration, boiler efficiency, water use, etc.)

The 2 m^2 difference in solar aperture between the single and dual aspect designs, equivalent to about 500 kWh/yr, is also quite compatible with other measured results, bearing in mind the higher heat loss of the single aspect design and the low statistical certainty.

Since the solar apertures have been worked out using measured ΔT 's, these increased solar contributions will assume any increase in internal temperature over the heating season to be all useful. Also, the difference in solar aperture between the single and dual aspect houses may be in part an effect of the different placing of the external temperature probes, mentioned in the previous section.

6.3.3 Low Solar Method

The triaxial method can be simplified into two dimensions (thus producing printable graphs) by essentially ignoring the solar gains and using only dull weeks. Also, given that the researchers are probably better at estimating the free heat gain term, K , than the regression automaton, it has been assumed to be known. This has allowed estimates of $\sum U.A + C_v$ to be produced for all the intensively monitored houses, and using values of C_v estimated from the pressure tests, values of the fabric heat loss alone, which can be compared with the theoretical values.

The first procedure used was to select from the winter 1981/82 data set all the weeks for which the solar radiation was less than 60 W/m^2 average ($1.5 \text{ kWh/m}^2/\text{day}$). This effectively guarantees that the solar gains are less than about 15% of the total energy flow. The energy balance equation then reduces to:-

$$Q + K = (\sum U.A + C_v) \cdot \Delta T$$

If values of $Q+K$ are plotted against ΔT , then the slope of the resulting line gives an estimate of the total house heat loss $\sum U.A + C_v$. To a certain extent this assumes that C_v (and $\sum U.A$) is constant and independent of ΔT , which we know is not really true. These problems are discussed further in the Rapid Thermal Calibration report.

Figure 6.12 shows typical plots for three individual houses, a Neath Hill insulated type and one each from Pennyland Area 1 and 2. The fit to a straight line is fairly satisfying, though it is clear that without assuming that the lines go through the origin (i.e. that K is known), the slopes would be rather uncertain. The data does seem good enough to distinguish the 'energy signatures' of the Area 1 and Area 2 houses and at a lower confidence level, those of Neath Hill and Pennyland 1.

By pooling the data from many houses a composite 'energy signature' has been built up for all the houses in an area for which there were more than 5 data points and for which the regression line was a good fit. The results are shown in Table 6.6 below.

Estimates of total heat loss have been made both from heat meter space heating data and from gas meter data for a larger sample. The results are similar and about 10% lower than theoretical values taking into account ventilation rates estimated from pressure tests (see section 4.6).

Table 6.6 Estimates of total house heat loss from regressions

Estate	Based on heat meter		Based on gas meter		Theoretical value
	Total loss	Sample	Total loss	Sample	Total loss
Neath Hill Insulated	181 ± 35	5	190 ± 17	14	218
Pennyland 1	169 ± 10	11	163 ± 7	16	196
Pennyland 2	132 ± 7	8	124 ± 6	6	143

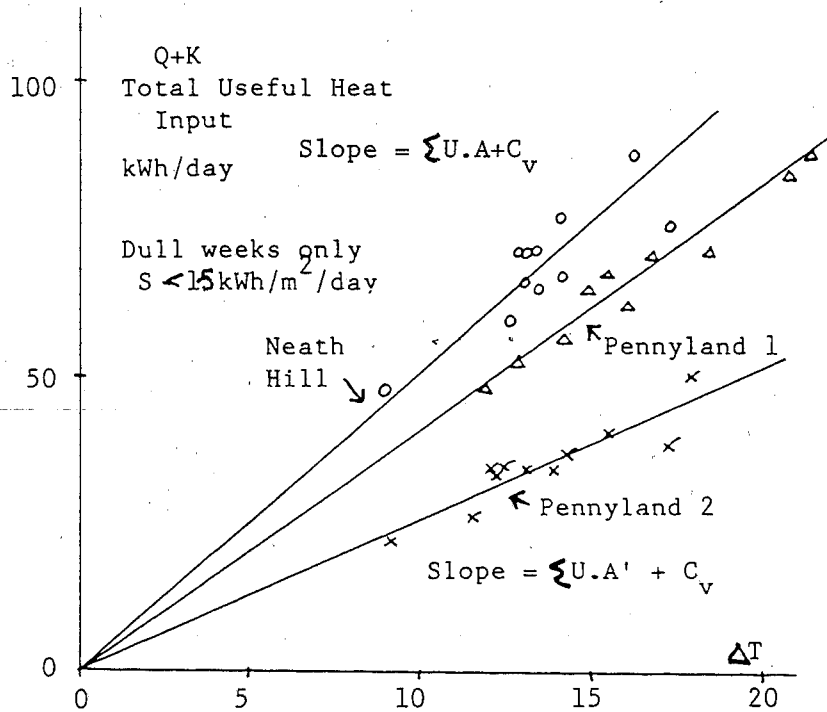
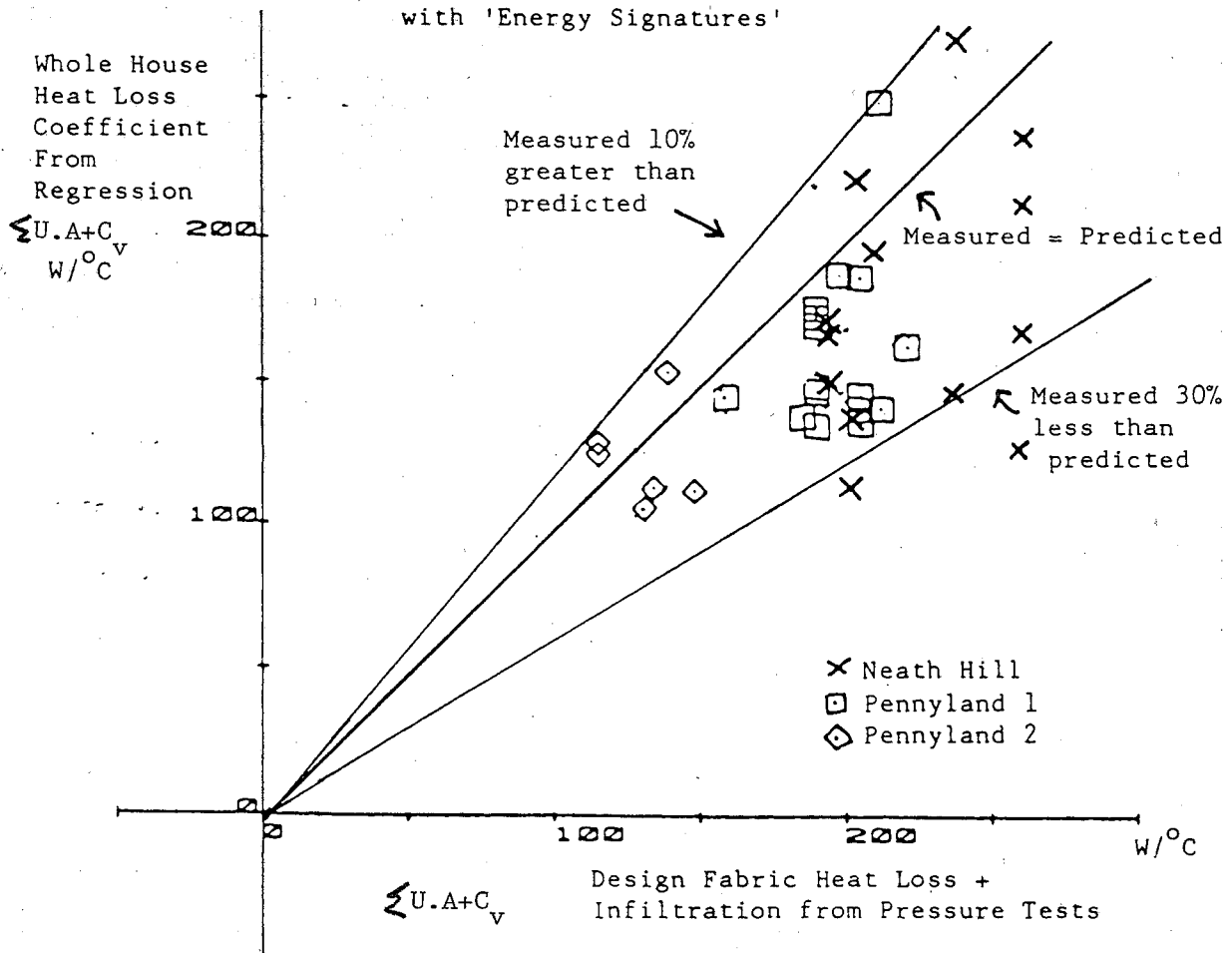


Figure 6.12 'Energy Signatures' of 3 different individual houses

Figure 6.13 Comparison of Design Heat Losses with 'Energy Signatures'



We can extend the process to individual houses. Figure 6.13 shows comparisons of values of total house heat loss calculated by regression with theoretical heat loss figures for individual houses from the three groups. Again there is a general tendency for the measured value to underestimate the predicted one by about 10%. The spread is from slightly under 30% less than predicted to 10% larger than predicted.

We would expect a slight underestimate, since there are still some solar gains that we have not taken into account. A large spread is also quite likely since there are heat losses from one house to another through the party walls. Also, we have extrapolated from a few pressure tests up to average ventilation rates for a large number of houses.

These heat loss differences also have annual energy consumption effects. These have been estimated using a simple monthly U-value model and are shown in Table 6.7 below:-

Table 6.7 Differences in specific loss estimates and their statistical significance (derived from Table 6.6)

	Neath H - Penny 1		Penny 1 - Penny 2	
	item	signific.	item	signific.
Based on heat meter				
specific loss diff.(W/K)	12±16	none	37±4	99%
equiv. energy (kWh/yr)	780±1040	none	2410±260	99%
Based on gas meter				
specific loss diff.(W/K)	28±5	95%	38±3.5	99%
equiv. energy (kWh/yr)	1820±325	95%	2470±220	99%

As will be shown in section 6.6, the energy savings calculated from the gas meter data agree well with results from other sources. These findings are important, since they support various field trials where this kind of 'energy signature' monitoring has been undertaken. Trials such as those at Birmingham (ref. 6.5) have attempted to calculate the energy savings of retrofit insulation measures by determining the energy signature of a house before and after modification, usually with only 8-10 weeks of measurements. The Pennyland results suggest that as long as a good energy signature can be obtained (which essentially means being able to measure energy consumptions in very cold weather) the calculated energy savings are likely to be reasonably accurate.

6.3.4 Siviour's Two-Dimensional Method

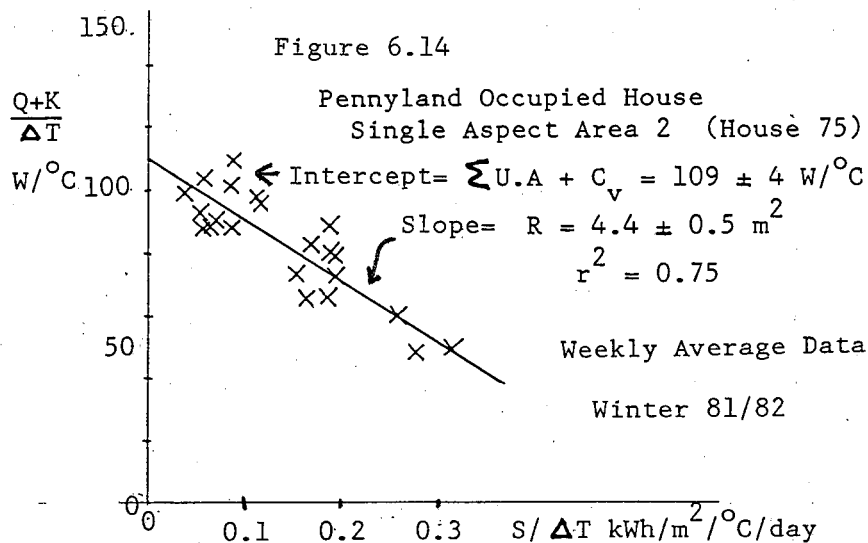
If the free heat gains, K , are known, then the heat balance equation can be rearranged in a way suggested by J.Siviour for house thermal calibration purposes (ref.6.6).

$$Q + K = (\sum U.A + C_v) \cdot \Delta T - R.S$$

transforms to

$$\frac{Q + K}{\Delta T} = \sum U.A + C_v - R.S / \Delta T$$

Thus by plotting $(Q+K)/\Delta T$ against $S/\Delta T$, we get a graph whose y-intercept is $\sum U.A + C_v$, the house total heat loss coefficient, and whose slope is R , the solar aperture. Figure 6.14 below shows such a plot for a Pennyland single aspect house:-



This type of plot has not been pursued in this project, but it has been used extensively in the Linford project. It makes a good alternative to the triaxial and 'low solar' methods, especially where good computer graphics allow the rapid drawing of graphs for visual inspection. This is very important where it is likely that the house performance is likely to be changing over the year, or as at Linford, where the floor heat loss created a large and unforeseen extra problem.

6.4 Energy Balances

Section 5.8 has already described energy balances for the intensively monitored house types. In this section we look at the self-consistency of the method. We can by making different assumptions either calculate the useful solar gains by remainder, or the house ventilation loss.

The method has built up an energy balance expressed as:-

$$\begin{array}{ccccccc} \text{Boiler} & + & \text{Incidental} & + & \text{Solar} & = & \text{Fabric} + \text{Ventilation} + \text{DHW} + \text{flue} \\ \text{gas} & & \text{gains} & & \text{gains} & & \text{loss} & \text{loss} & \text{loss} & \text{loss} \end{array}$$

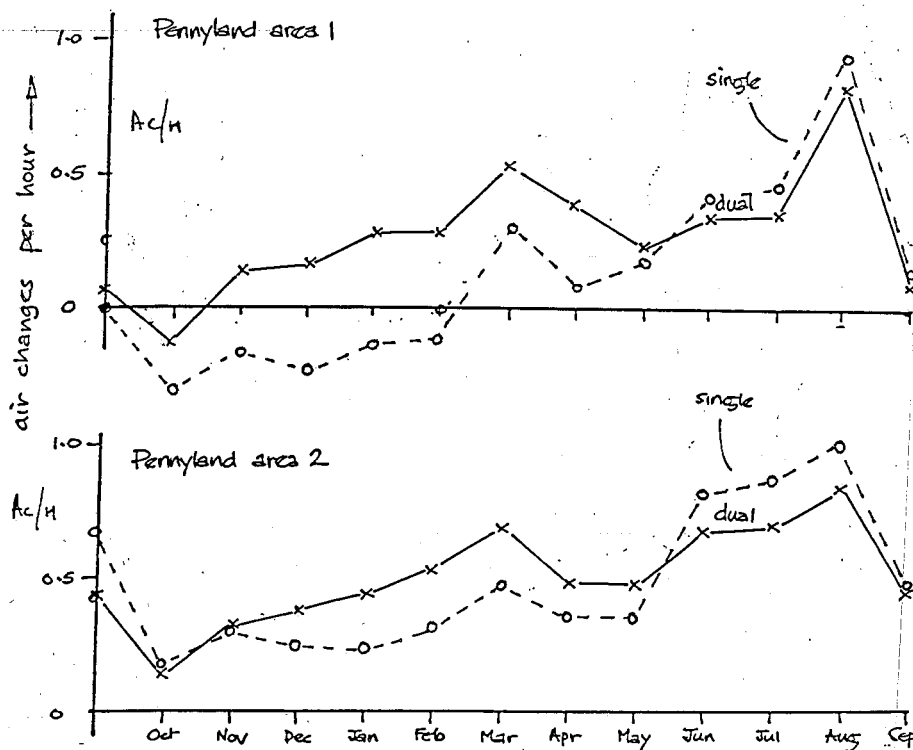
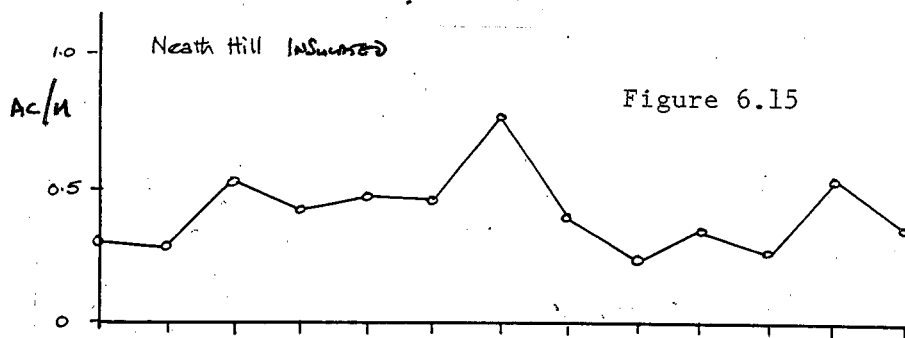
Each of these quantities could be estimated if we had information about all the others. Here we will look at estimates of solar gains and ventilation rates.

Item	Method of Estimation	
	Solar Gains as Residual	Ventilation Rate as Residual
Boiler Gas	Measured	Measured
Incidental Gains	From measured electricity, cooking, etc.	From measured electricity, cooking, etc.
Solar Gains	Residual	From regression solar aperture and incident solar
Fabric Loss	From I.H.V.E. Guide	From I.H.V.E. Guide
Ventilation Loss	From pressure tests	Residual
DHW Loss	From summer gas use	From summer gas use
Flue Loss	From sample measured boiler efficiencies	From sample measured boiler efficiencies

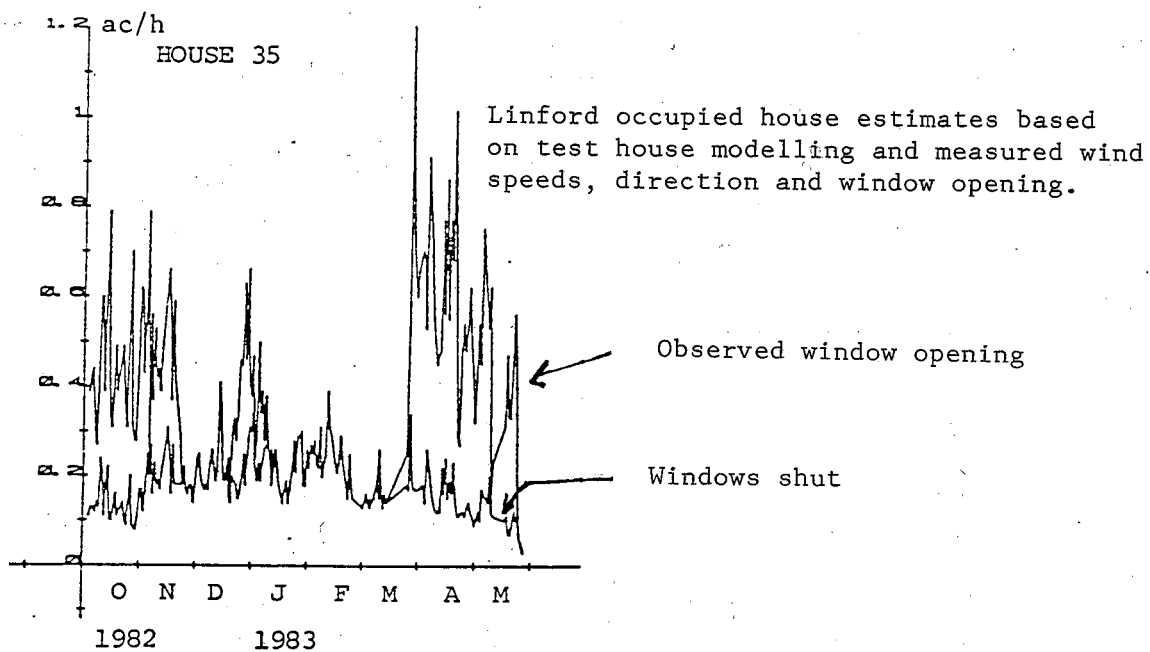
6.4.1. Ventilation rates as residual

Figure 6.15 shows the air change rates derived from the estimated ventilation heat losses as residuals. As, expected, there is a lot of 'noise' mixed up with the estimates, sometimes leading to negative values. This can be put down to measurement errors and also the presence of other factors not included, such as the floor heat loss, which as measurements at Linford have shown tends to lag about a month behind the house fabric heat loss.

The winter estimated ventilation rates are consistent with the average values assumed from pressure tests and the Pennyland data shows a distinct increase up to about 1 ac/h in summer. For comparison more detailed estimates based on Linford test house measurements and occupied house window opening data are also shown. This give a similar picture of a low winter ventilation rate rising at the end of the heating season.



Ventilation rates calculated by remainder from energy balance using fixed solar aperture.



6.4.2 Solar Gains as Residual

This method of analysis was mooted for a Europe-wide assessment survey of passive solar houses (ref.6. 7). It is thus important to understand how vague the answers are and how sensitive to other assumptions about the energy use of the house.

Figure 6.16 shows estimates of solar gains into the house both by the 'fixed solar aperture' method and by the 'residual' method. While the heating season average figures show some correspondence for each house type, the month-to-month variations seem totally clouded by noise.

The good results from the Linford occupied houses suggest that the fixed solar aperture method is likely to produce reasonable answers, at least consistent with those obtained from the test house experiments. The residual solar method relies rather dangerously on getting all the other energy flows in the house right. For example an increase in assumed air change₂ rate of 0.25 ac/h for a Pennyland Area 2 house is equivalent to a 2.8 m² increase in solar aperture (i.e. 50%). Simplistic assumptions about ventilation rates (such as assuming 1 ac/h) would thus make total nonsense of the residual solar gains.

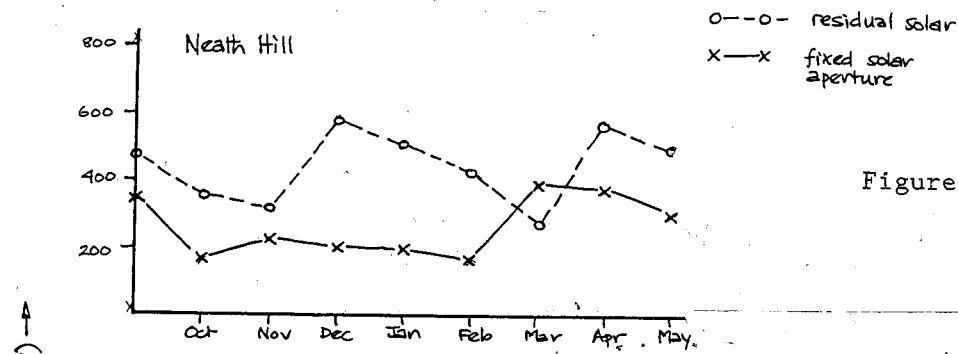
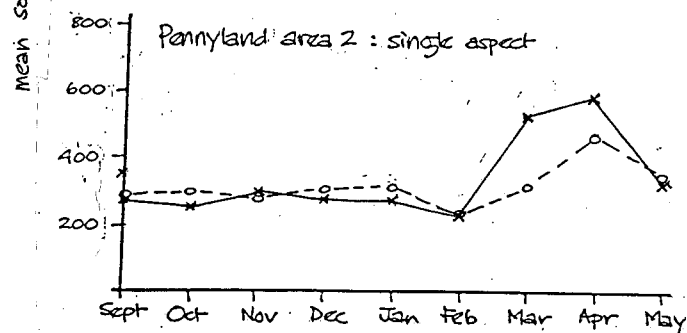
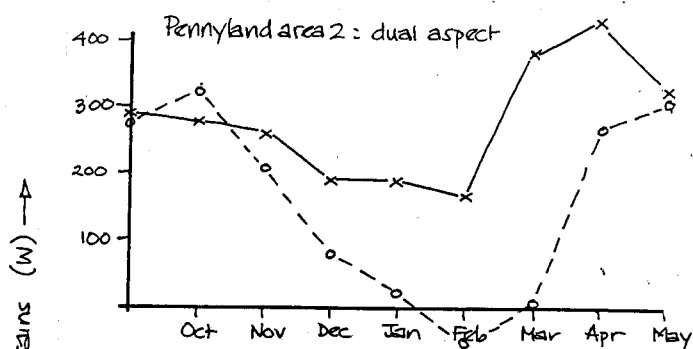
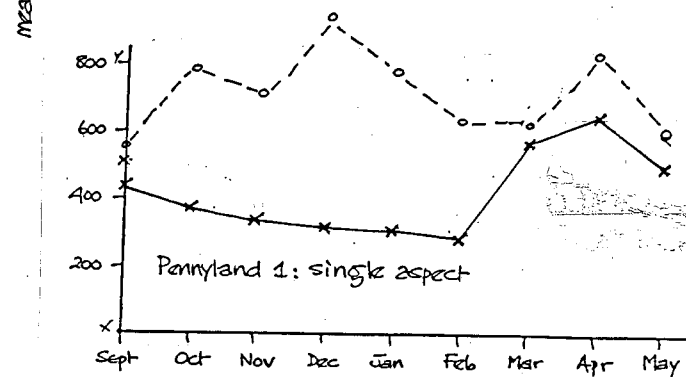
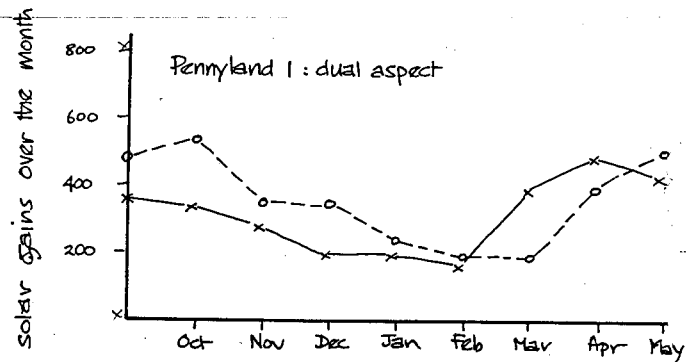
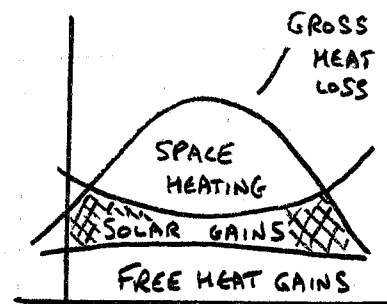


Figure 6.16



Comparisons of estimates of solar gains from the residual solar (o---o) and fixed solar aperture (x---x) energy balances.



x--x fixed aperture
o--o solar residual

6.5 Extending the Design Modelling

The Pennyland project started with a modelling and design exercise carried out over 1977 and 1978. The modelling suggested that significant energy savings would result from insulating houses to the levels of Pennyland 1 and 2 and from passive solar design measures. The exact size of these savings was however sensitive to the assumptions made about the way the houses were used, and for this reason alone were uncertain (there are also uncertainties which arise from basic limitations in the model itself).

The Pennyland and Linford projects have confirmed the crudest of the predictions of the earlier modelling work, but for a variety of reasons (as we have seen above) cannot provide answers to some of the more subtle questions. For example, the effect of the great attention that was paid to avoiding overshadowing and facing the houses south at Pennyland compared with Neath Hill is lost in a host of more important differences - heating system design, infiltration rates, room layout and the large differences between the two basic house types at Neath Hill. Nevertheless, the Pennyland and Linford projects can provide better estimates for many of the quantities eg. internal temperatures, ventilation rates, effective solar apertures, which were not well known in the first round of modelling work. By feeding estimates for these quantities based on the empirical measurements back into the modelling, we can produce a theoretical synthesis of the experimental data. In a sense this step is one of model calibration.

This synthesis can follow the comparisons originally intended, rather than having to compare 'real' house designs that may differ in several ways at once. The process is thus one of taking a 'unified' Pennyland/Neath Hill house shell through various energy saving steps to progress from the uninsulated Neath Hill house type up to the Pennyland Area 2 houses.

This step process will also be used in the next chapter to work out the cost implications of each step and the resulting cost-effectiveness.

Because of this attempt to unify the two estates there are slight discrepancies between the costing/computer modelling representation of a house shell and its real form. Some of these are in the interests of following the steps, others are due to the limitations of the NBSLD program as set up (such that it would only accept 25 mm increments of insulation thickness). Further discrepancies occur in the next chapter on costings, in the interest of producing cost-effectiveness figures relevant to current U.K. construction practice.

The savings have been calculated in three parts:-

1. Insulation and air infiltration savings from the Neath Hill uninsulated group through to Pennyland Area 2. These savings have been calculated for a 'normally overshadowed and oriented' dual aspect house. The subject of solar 'normalcy' will be discussed below.

2. Marginal passive solar energy savings, resulting from the avoidance of overshadowing, correct orientation, concentrating glazing on the south side, and the change of design from dual aspect to single aspect.
3. Boiler efficiency savings, translating the useful energy consumptions calculated above into actual gas delivered energy.

These basic steps are shown in figure 6.17

6.5.1. Insulation and Infiltration Reduction Savings

The NBSLD program has calculated the annual useful space heating consumptions for a dual aspect end-of-terrace house, taking it through the steps from the 1976 Building Regulations insulation standard up to the Pennyland Area 2 insulation level. The house is assumed to face south-west, be a true dual aspect design, i.e. with equal areas of glazing on both facades. Other details are given below:-

Element	Area m ²
External Wall	93.7
Windows	12.1
Doors	3.8
Floor/Roof	49.2

Heating 9 hrs/day - Thermostat setting 19°C
 Internal free heat gains 16 kWh/day
 Net curtains.

The weather data used for the model is Kew 1969, which has a slightly warmer average winter temperature than the Milton Keynes 81/82 data relating to the actual measurements. Solar radiation data for the two years is similar. Further details of the model will be found in reference 6.8.

For the purposes of calculation, the Neath Hill houses are assumed to have a constant ventilation rate of 0.6 ac/h and the Pennyland ones 0.35 ac/h. This choice of values perhaps slightly understates the savings assessed from pressure test results, having been taken more from Linford infiltration calculations than those given in Appendix 7. The differences are not likely to be very significant.

The calculated energy consumptions are shown in Table 6.9 and the savings between groups, in useful space heating energy, shown in a matrix form.

The table shows that the largest energy savings are due to wall insulation, with another large contribution from the reduction of air leakage. The addition of thermal mass to the design increases energy consumption, principally due to the poorer external wall U-values resulting from the use of a dense concrete inner leaf.

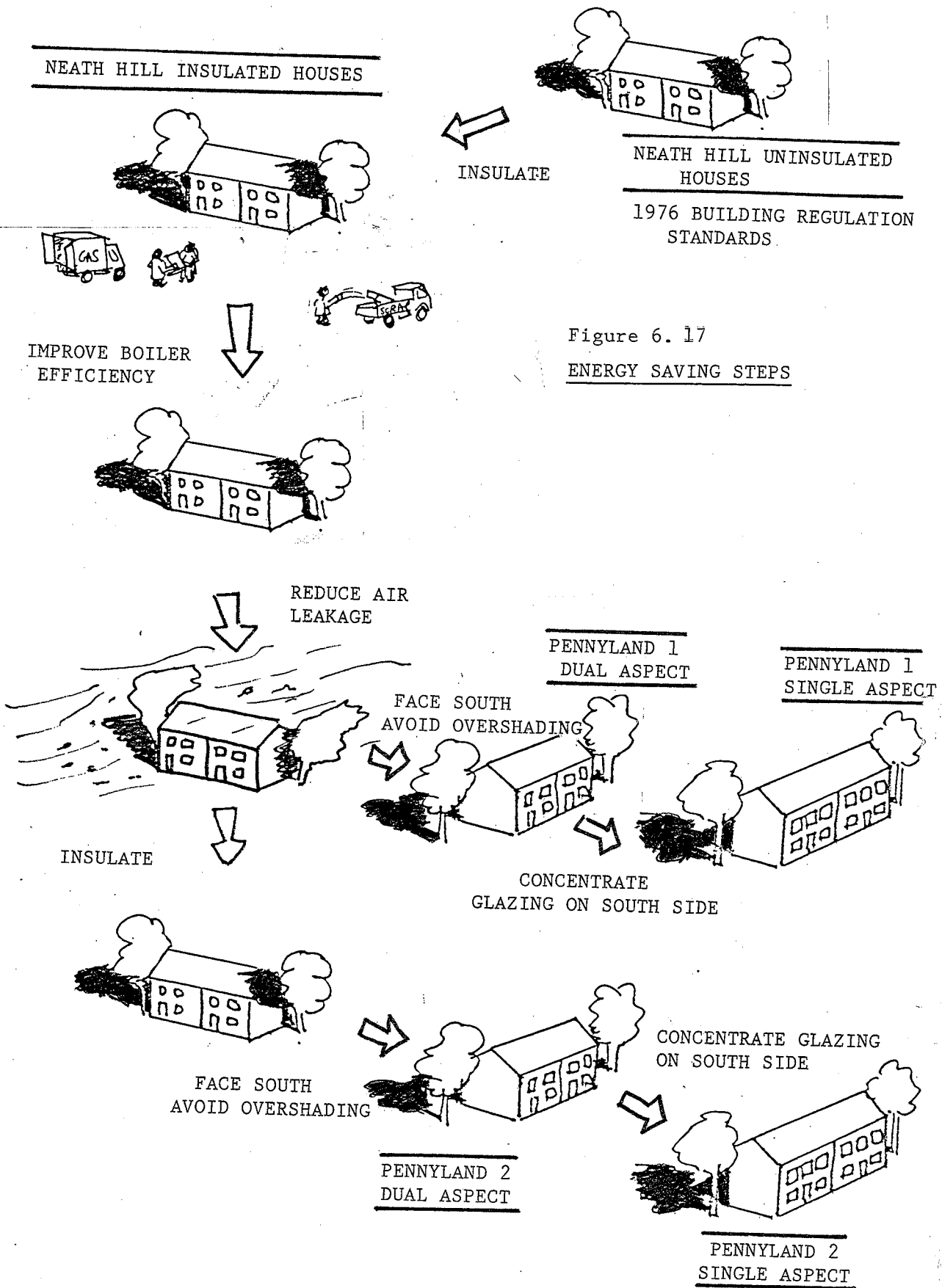


Figure 6. 17
ENERGY SAVING STEPS

Table 6.9

Pennyland reference house insulation and infiltration savings.				
	whole house heat loss W/K	fabric loss W/K	annual space heating kWh/a	useful energy saving kWh/a
Neath Hill uninsulated 1976 regulations Unfilled cavity walls 50mm roof insulation Single glazing U=4.3 W/m ² K Ventilation rate 0.6 ACH	266	216	9135	-
Neath Hill insulated. As above + 50mm wall cavity insulation	222	172	7180	1955
Add 25 mm roof insulation	214	164	6768	412
Add thermal mass	223	173	7359	-591
Pennyland Area 1. Approx 1982 building regulations Ventilation rate reduced to 0.35 ACH	202	173	6238	1121
Roof insulation 75 to 150mm	193	164	5675	563
Double glazing U=4.3 to 2.5	171	142	5055	620
Wall insulation 50 to 100mm	149	120	3907	1148
Pennyland Area 2 As above + floor edge insulation. U=0.61 to 0.46	141	112	3611	296

Insulation and infiltration savings matrix.				
kWh/a	Pennyland 2	Pennyland 1	Neath Hill insulated	Neath Hill uninsulated
Pennyland 2	0	2627	3569	5524
Pennyland 1		0	942	2895
Neath Hill insulated			0	1955

6.5.2. Marginal Passive Solar Gains

The house shell used for the insulation energy savings calculations has been taken to be 'normal' from a solar point of view. It is a little difficult to define a 'non-solar' house, especially in terms of overshadowing. In this case it has not been done with reference to the Neath Hill houses, but to a wider survey of the Cambridge housing stock carried out by the Martin Centre (ref. 6.9).

This survey was intended to evaluate the potential for retrofit passive solar measures, but is a good record of typical site conditions. It involved the analysis of hundreds of photographs taken from a height of 1.2 metres above ground in front of houses, showing the solar obstructions. The shading profiles of surrounding buildings and trees were turned into a figure for the percentage reduction in solar radiation over the assumed heating season of October to May.

Table 6.10 below shows a breakdown of average solar transmission by age and type of dwelling. For new construction, we are obviously interested in the bottom line. This shows a wide spread of values. Detached houses, in particular, are badly overshadowed and become progressively more so with age. This is almost entirely due to the surroundings of mature trees. This is likely to be the eventual fate of both the Linford and Pennyland houses. For houses with low levels of overshadowing, the obstructions are most likely to be other buildings.

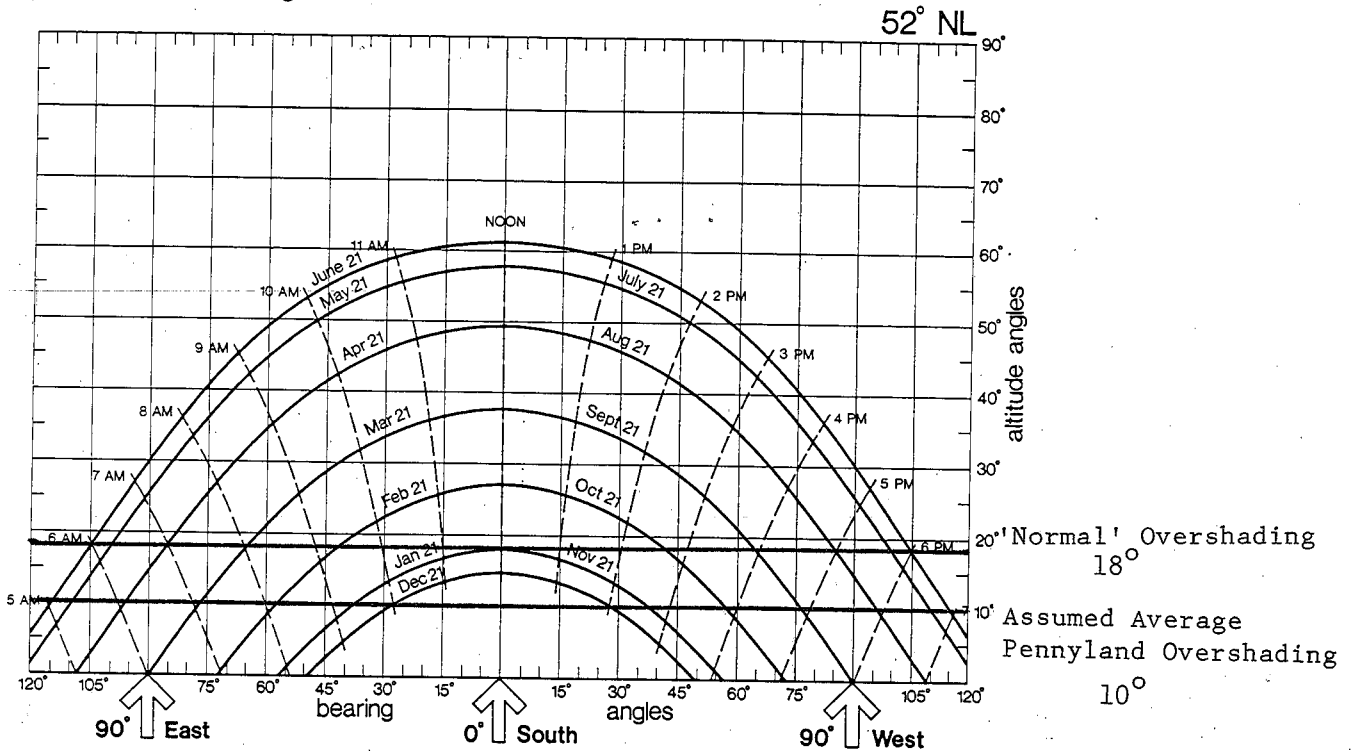
Table 6.10 Overshading by Building Type and Age - Cambridge Survey

Average Percentages of received solar radiation* per type of dwelling and age group

Age Groups	Ter.	Ter.	Semi	Det.	Bung.	Fl< 5fl	Fl> 4fl	Maison.
Groups		end	det.					
Before 1900	84	86	64	51	100	93		
1900-1919	87	92	90	93	-	-	-	-
1919-1939	93	95	92	81	100	100	-	-
1939-1963	94	95	95	88	-	96	-	99
1963-1969	92	93	91	86	96	96	-	78
1970-	82	99	90	84	92	84	100	-
Average	88	93	92	81	96	94	100	86

*Received radiation = obstructed radiation/unobstructed radiation on South-facing vertical surface, October-May.

Figure 6.18



Overshading
angle

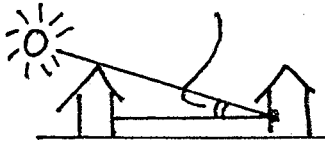
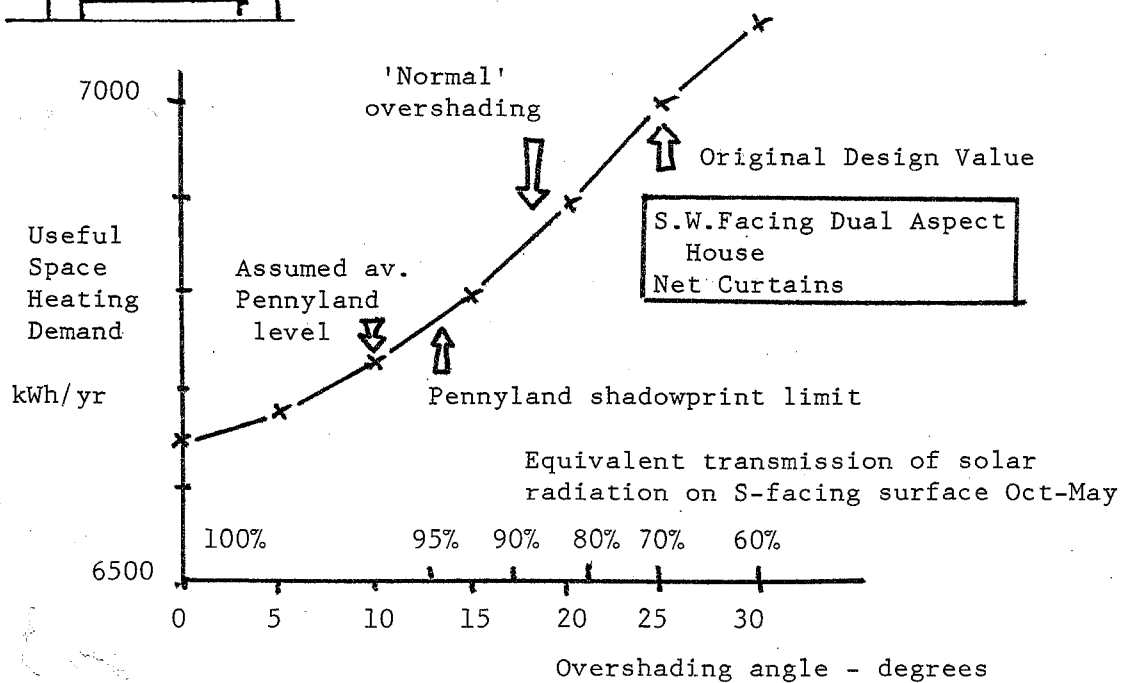


Figure 6.19
Effects of Overshading on Space Heating Demand



For the purposes of calculations, an average transmission of 90% has been taken. This corresponds to an overshadowing angle of 18° , i.e. the sun's direct rays are obstructed below this solar altitude. As shown in Figure 6.18, these means that no direct solar rays will enter the ground floor windows over a period of two months in mid-winter.

The actual Pennyland overshadowing level has been taken to be equivalent to an overshadowing angle of 10° . The design shadowprint used in laying out the estate is equivalent to an overshadowing angle of 13.5° , but most of the houses are better than this. A figure of 10° has also been used for the more extensive calculations carried out in the Linford report. In practice, it is likely that this figure will worsen over the years as the trees in the Pennyland estate mature.

Also, for calculation purposes, it has been assumed that all solar gains are effectively taken at ground floor window height and subject to overshadowing effects. Obviously solar gains to upstairs windows would not be so badly obstructed, but it is not really clear what the relative usefulness of upstairs solar gains are to downstairs ones. This is an area where modelling of a more complex nature would be useful.

The importance of overshadowing on house energy consumption can be seen in figure 6.19, showing the calculated space heating demand of a south-west facing dual aspect house as a function of the overshadowing angle and consequent percentage solar transmission. The precise definition of 'normal' overshadowing is thus quite important in making comparisons. One of the conclusions of the Cambridge survey was that overshadowing did not seem to be as bad as was originally thought. The angle of 18° used for calculations here is somewhat less than the figure of 25° taken in the original design calculations, largely from observed conditions around the Bradville solar house.

Defining a 'normal' house orientation for calculations is somewhat simpler. The calculated variation of house space heating with orientation for an overshadowed house is fairly small, (see figure 2.4), therefore for modelling purposes south-west has been taken as 'normal' orientation.

Solar absorption for the model has been based on results from the Linford test house. Here tests were carried out to determine the effective solar aperture of the house with and without net curtains and before and after insulating the ground floor slab. Solar gains were generally somewhat less than originally estimated due to considerable reflection from the interior of the house.

For the purposes of calculation all houses have been taken to have full net curtains with appropriate levels of solar gains.

The almost universal use of net curtains in the Pennyland estate has been a source of much disappointment. A glance at the various photos of the houses in this report will show that nearly all the windows appear white and not black. Most are actually lighter than the surrounding brickwork, implying a solar absorptance of 50% or less.

Even worse, there was an extensive tendency for blinds and shutters to be left drawn on sunny winter days. For example, in the photograph figure 2.6, there are six windows visible. Only one is unobstructed, three have full net curtains and two have the paper blinds firmly drawn.

In the social survey, 35% of Pennyland residents admitted to drawing blinds or shutters on sunny winter days. A count of windows made in March 1983 showed that 80% had full net curtains and less than 10% had no obstruction at all.

It is likely that this level of window obstruction is partly a glare problem—that could perhaps be dealt with by better window design, but mostly a privacy one. The fact that photographs such as figure 6.20 can be easily taken from the street or public pathway makes this clear.

The Linford houses, which are not overlooked from the south had only a 50% use of net curtains and consequently higher solar gains. Dealing with this privacy problem in estate design would probably increase the solar gains but might be extremely difficult to engineer.

Energy Calculations

The NBSLD program has been used to assess five house types at the two different Pennyland insulation levels:-

- House A. True dual aspect house shell with equal glazing on both facades. Net curtains. 'Normally overshadowed', faces S.W.
- House B. As above but south-facing and with reduced overshadowing. Overshading angle 10° .
- House C. Pennyland dual aspect house design. As above but with 1.35 m^2 of window area brought from the north facade to the south. North facing window area 4.7 m^2 , south 7.4 m^2 .
- House D. Pennyland single aspect design. Same floor area as dual aspect design, but built to a shallow plan with more total glazing area and most concentrated on the south facade.

External wall area	88.8 m^2
South-facing window area (including glazed door)	13.6 m^2
North facing window area	3.9 m^2
Unglazed door area	3.9 m^2
Net curtains	
Other details as above	

- House E. Pennyland single aspect design but with no window clutter.

The energy consumptions of these different house types are shown in Table 6.10 together with the savings expressed as a matrix form.

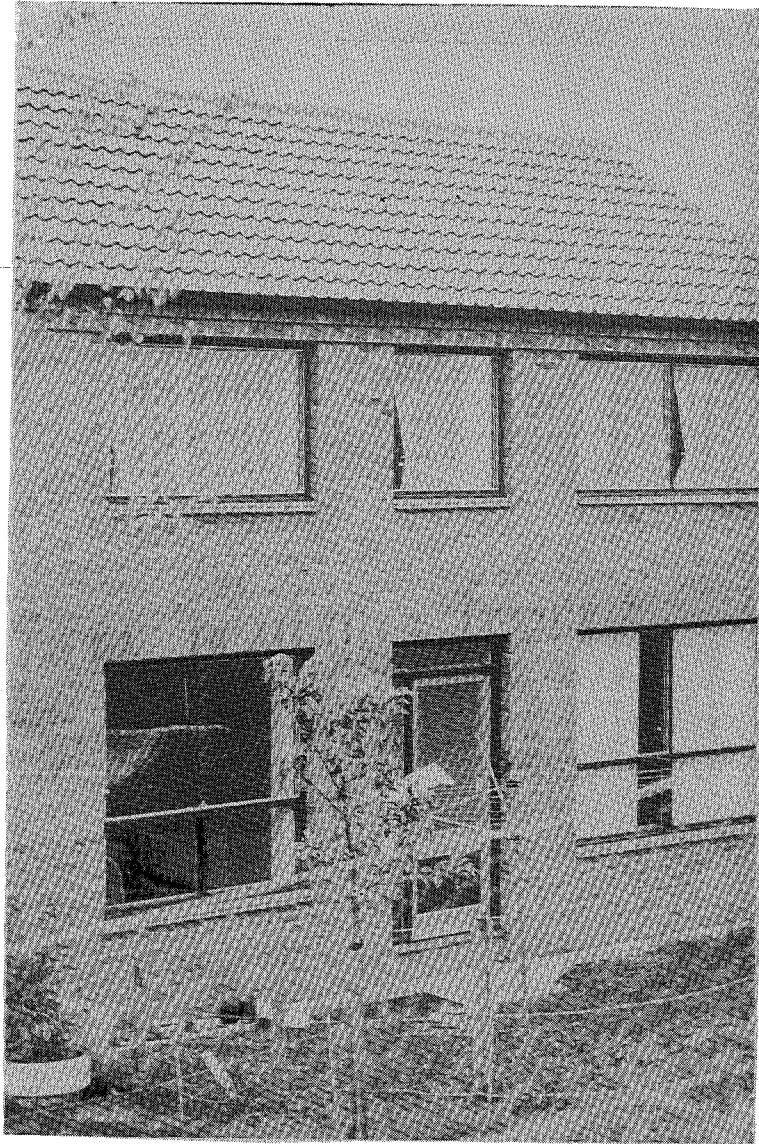


Figure 6.20

The presence of net curtains (upper floor) or drawn blinds (downstairs right) dramatically reduces the window solar absorptance. Less than 10% of south-facing Pennyland windows had no obstructing curtains.

Table 6.10

Passive solar design savings.					
House type	Area 1		Area 2		
	aux space heat kWh/a	saving kWh/a	aux space heat kWh/a	saving kWh/a	
A. True 'dual aspect' S.W. facing, over- shaded, net curtains	6238	-	3611	-	
B. True 'dual aspect' South facing, reduced overshading, net curtains	6052	186	3442	169	
C. Pennyland dual aspect South facing, reduced overshading, net curtains	5937	115	3354	88	
D. Pennyland single aspect South facing, reduced overshading, net curtains	5957	-20	3345	9	
E. Pennyland single aspect South facing, reduced overshading, no window clutter	5621	336	3104	241	

Solar savings matrix. Pennyland area 1 insulation.					
	A	B	C	D	E
B	186	0			
C	301	115	0		
D	281	126	-20	0	
E	617	431	316	336	0

Solar savings matrix. Pennyland area 2 insulation.					
	A	B	C	D	E
B	169	0			
C	257	88	0		
D	266	97	9	0	
E	507	338	250	241	0

The marginal solar savings of the Pennyland dual aspect houses in relation to the 'normal' Neath Hill houses amounts to about 300 kWh/yr of useful space heating energy. Of this about 200 kWh/yr is due to the avoidance of overshadowing and correct orientation and 100 kWh/yr due to the slight shift of glazing from the north facade to the south. These results apply at both Area 1 and Area 2 insulation levels.

There will also be very slight increases in average internal temperatures as a result of these changes, but these have not been assigned any usefulness by the program.

There appears to be no difference in energy consumption between the single and dual aspect types. Although the single aspect houses have larger solar inputs, these are just used to offset the increased heat loss of the design.

Comparison with original estimates

These results are considerably less than originally estimated. The avoidance of overshadowing and correct orientation were originally estimated to save 700 kWh/yr of useful space heating. The large reduction is due to both the low solar absorptance due to the use of net curtains and the redefinition of 'normal' overshadowing.

The original estimate of the dual aspect-single aspect difference was 200 kWh/yr. The fall to zero is simply due to the lower solar absorptance. Marginal passive solar gains could still potentially be reasonably large, as demonstrated by the 'reduced window clutter' figures. There is potentially an extra 300 kWh/yr for a single aspect house type if only windows could be made good solar absorbers.

These figures are, of course, totally dependent on the solar absorption figures measured in the Linford test house and any errors made there will affect these answers. For details of these measurements and the problems involved, readers are referred to the Linford project report.

6.5.3 Boiler Efficiency Savings

Finally, the useful space heating figure from tables 6.9 and 6.10 are brought together with an assumed useful water heating consumption of 2850 kWh/yr and the boiler efficiency plots of figure 6.21 to give the total house boiler gas energy consumptions.

For ease of tabulation the boiler standing losses (pilot light, etc.) have been expressed as an equivalent useful energy which can then be converted to delivered energy by multiplying by the marginal boiler efficiency.

Table 6.11 shows the total delivered energy consumptions of the various house types and the reductions in house heat loss accompanying them. These figures will then be taken forward into chapter 7.

The contents of Table 6.11 are plotted in figure 6.22, basically in useful energy, but convertible into delivered energy by using the left and right hand scales.

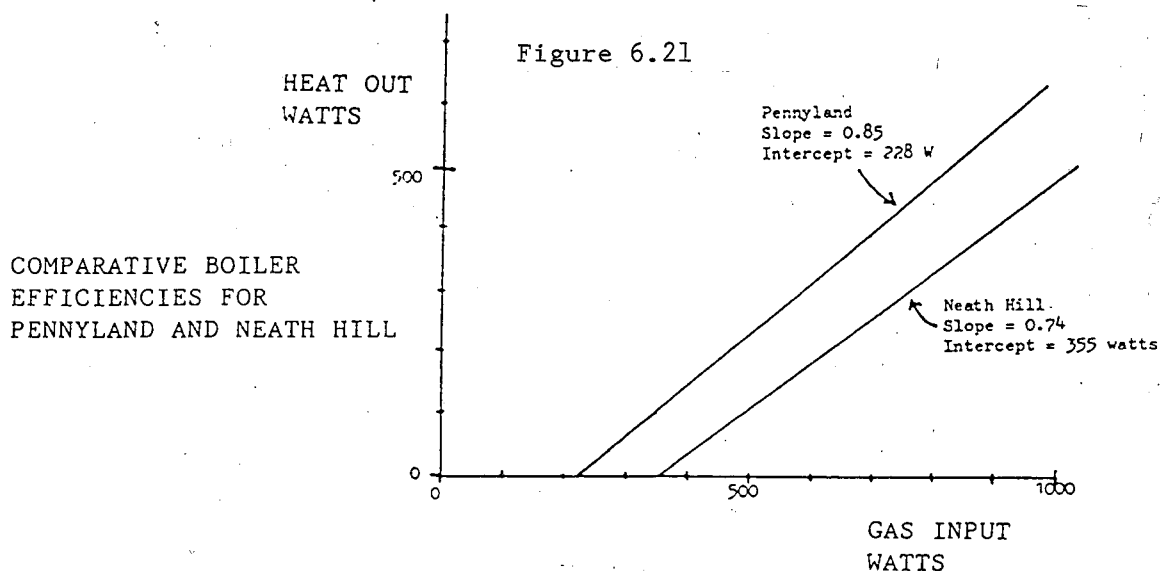


Table 6.11

PENNYLAND ENERGY
SAVINGS

All units are
kWh/yr

Useful Space Heating	9135	7180	7180	6768	7359	6238	5947	5621	5675	5055	3907	3611	3345	3104
Water heating & tank losses	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850
Boiler standing losses	2300	2300	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700
Total Equivalent Useful Energy	14285	12330	11730	11318	11909	10788	10547	10211	10225	9605	8457	8161	7895	7701
Total Delivered Energy	19304	16662	13800	13315	14010	12691	12408	12012	12029	11300	9949	9601	9288	9060
Delivered Energy Saving	-	2642	2862	485	-695	1319	283	396	661	729	1351	348	313	228
Reduction in Fabric Heat Loss W/°C	-	44	-	8	-9	-	-	-	9	22	22	8	-	-

Neath Hill
Uninsulated

Neath Hill
Insulated

Boiler

Roof Insulation
50mm-75mm

Add thermal
mass

Reduce vent.
rate

Pennyland 1
+ Marg. solar gains

Reduce window
clutter

Roof insulation
to 150 mm

Double glazing

Wall insulation

Floor insulation

Pennyland 2
+ Marg. Solar Gains

Reduce window
clutter

← 74% →
marginal efficiency

← 85% →
marginal efficiency

COMPUTED ENERGY SAVINGS FOR A DUAL ASPECT
END-OF-TERRACE HOUSE

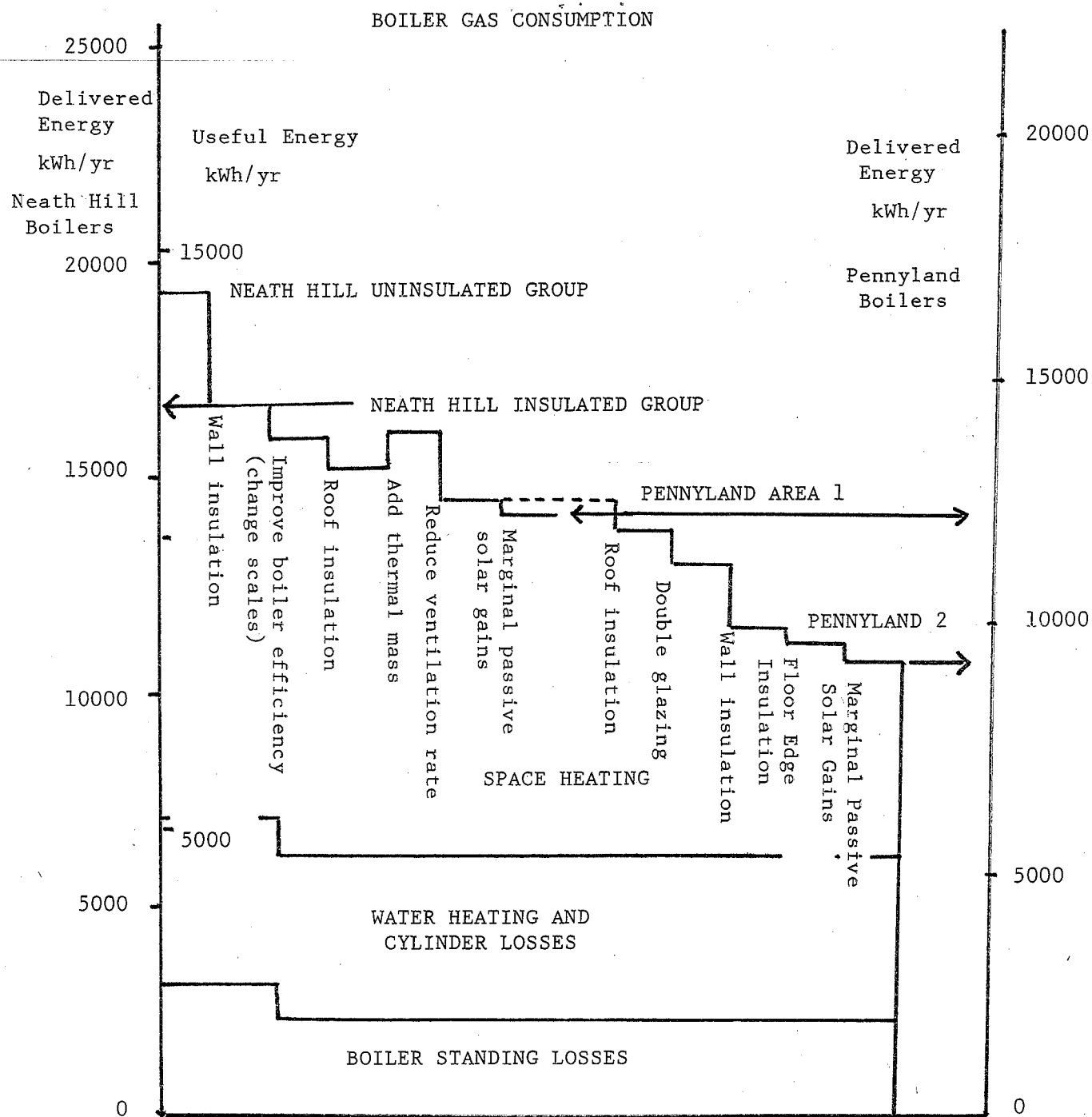


Figure 6.22

6.6 Summary and Comparisons of Energy Savings

This section is an attempt to reconcile the modelling and experimental results. This is in order to provide the most credible estimates of energy savings which will be used to work out the cost-effectiveness in the next chapter.

In this chapter energy savings have been calculated by a variety of methods:-

1. Refined and statistically processed annual gas consumptions
2. Modelling using the updated NBSLD design model.
3. Simple modelling from measured differences in the house heat losses.

Results from the first two methods will be taken forward into the next chapter.

6.6.1. Credibility of NBSLD model

First it is necessary to assess the credibility of the NBSLD model in producing similar annual energy consumption figures to those measured. Unfortunately, time did not permit the production of a suitable hourly weather data file for 1981/82. This would have allowed the NBSLD model to be used with the same weather data as applies to the actual measurements. It has instead been necessary to use the Kew 1969 weather data used in the original design process. The winter of 81/82 was slightly colder than the Kew data, with about 200 more degree-days. This temperature difference requires a correction of about 1000 kWh/yr to the computed space heating estimates.

Comparisons of modelling and measurement for the Linford project have shown that getting good agreement within about 1000 kWh/yr is very difficult. Occupant behaviour has a very large effect and it is difficult to describe in a simple way suitable for a model. For example free heat gains from cooking, lighting, etc., are not constant over the year, but tend to peak in mid-winter (see Linford report). Ventilation losses may vary enormously over the heating season with window opening.

Figure 6.23 shows computed and measured estimates of annual space heating consumption for the five intensively monitored house groups. The agreement is fairly close, considering statistical uncertainties. The minor differences in energy savings between groups will be dealt with below.

Figure 6.24 shows computed and measured annual gas consumptions for the four main insulation groups. The computed values, taken from Table 6.11 have been given an additional 1000 kWh/yr average gas cooking consumption. Again the agreement is reasonable considering the statistical spreads.

The detailed credibility of the NBSLD model as used in this project, is mostly dependent on the Linford project results. No formal 'validation' has been carried out, since this is an enormous task, but the model has demonstrated an ability to produce similar energy flow patterns to those actually measured.

Figure 6.23

Comparison of Measured
and Computed Space
Heating Demands

Measured data corrected
to common internal
temperature



Predicted from
NBSLD model with
correction for
degree-day difference

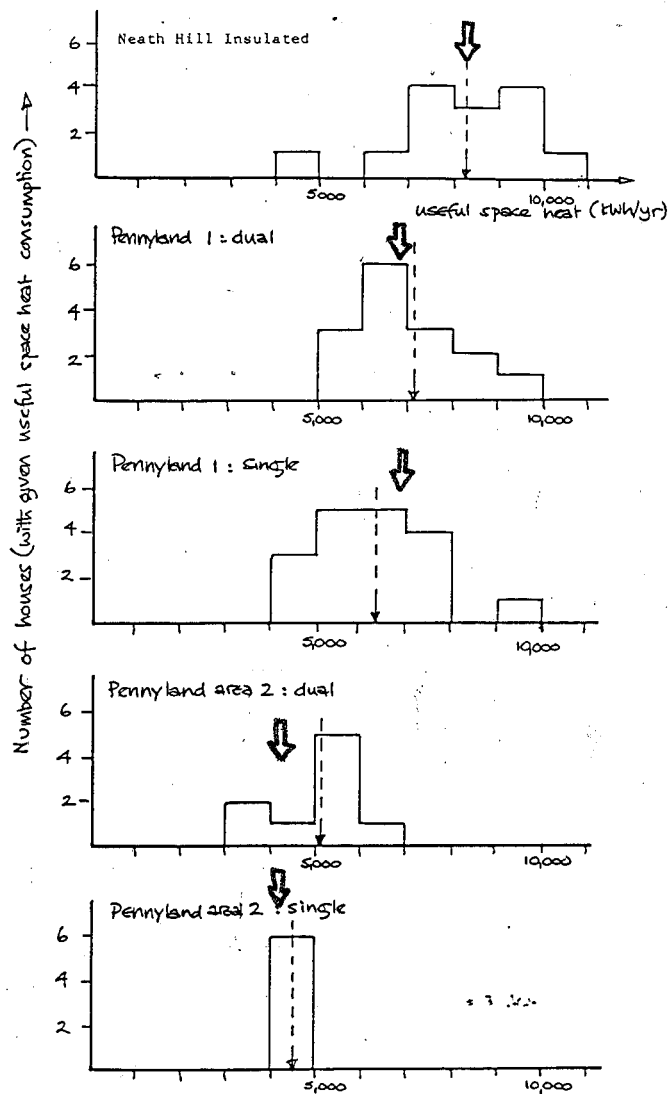
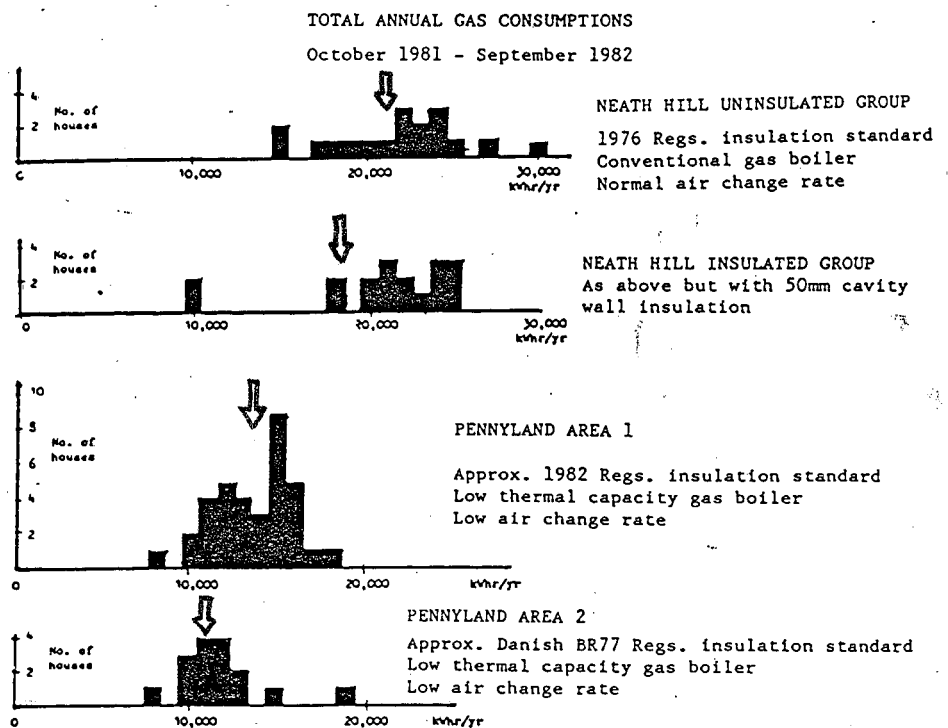


Figure 6.24

Comparison of
Measured and
Computed Annual
Gas Consumptions



Predicted from
NBSLD model
corrected for
difference in
degree days
and cooking use.



6.6.2. Summary of Energy Savings

We can now bring together the various estimates of the energy savings between the groups, made by different methods and with different assumptions. These savings with their standard errors (i.e. 70% confidence limits) are shown in figure 6.25. The 95% confidence limits are at approximately twice the standard error spread.

Neath Hill Uninsulated - Neath Hill Insulated

Saving from annual gas consumptions	2500 \pm 1700	kWh/yr delivered
Saving from NBSLD model	2642	kWh/yr delivered

This is a poorly controlled comparison since the only data available on the uninsulated group is quarterly gas bills. The main aim of the comparison was to check on the 'normalcy' of the Neath Hill Insulated group, but there is a high probability of a genuine energy saving.

Neath Hill - Pennyland Gas Boilers

Savings from measured efficiencies and consumptions	3400 \pm 1300	kWh/yr delivered
Savings from measured efficiencies and computed consumptions	2862	kWh/yr delivered

This saving is the large single one in the whole project. Although there is a fairly large standard deviation associated with this estimate, we have fair confidence in the result because of the good agreement with British Gas boiler studies. The difference in energy saving between the two estimates is due to slightly different assumptions of hot water use and the warmer weather data used in the NBSLD model.

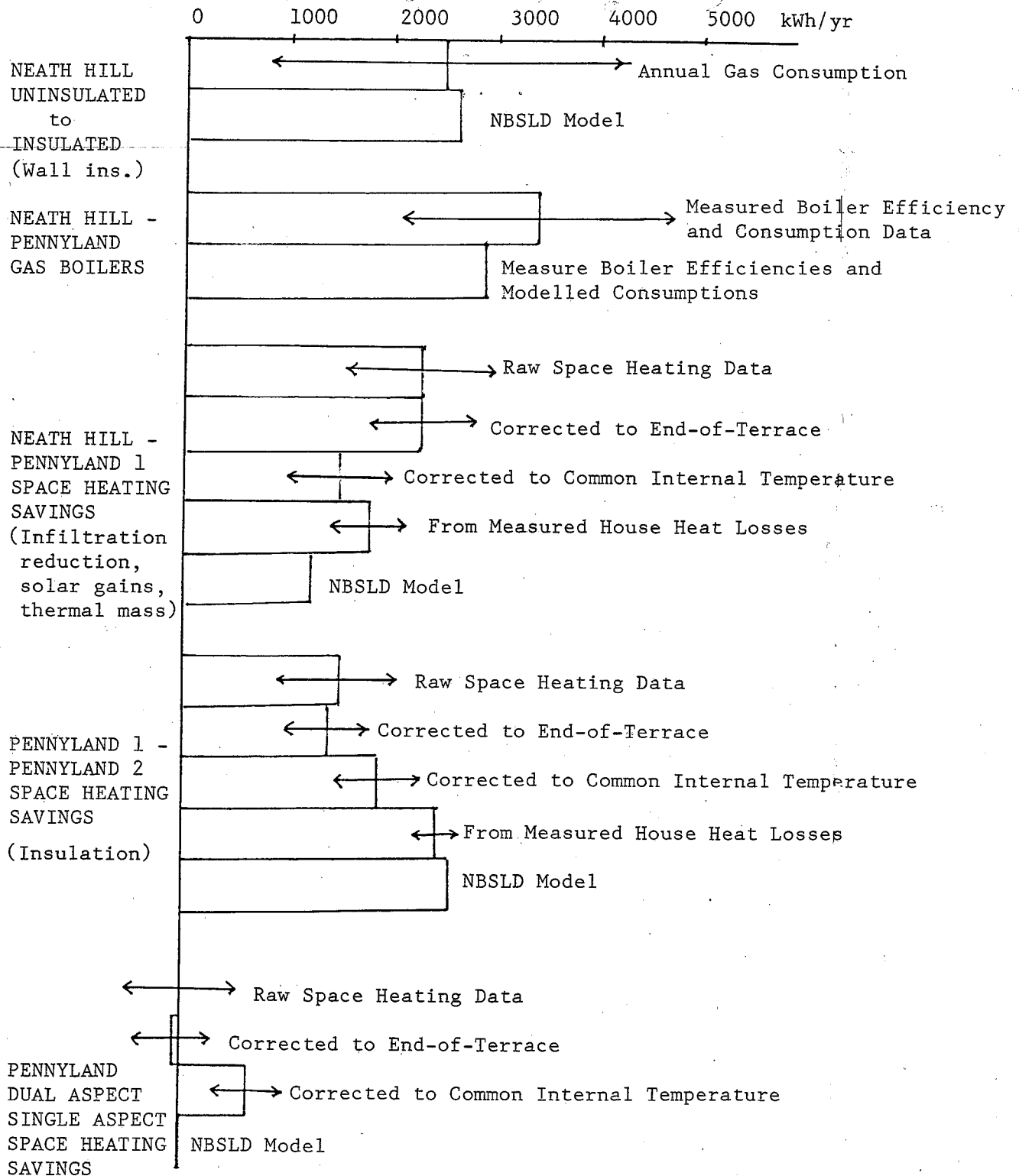
Neath Hill - Pennyland 1

		kWh/yr useful
Annual space heating analysis	- raw data	2300 \pm 720
	- corrected to end-of-terrace	2300 \pm 490
	- corrected to common temperature	1500 \pm 490
From measured house heat losses		1820 \pm 325
From NBSLD model		1233

In the original design estimates, this step was expected to produce a saving of about 700 kWh/yr, just due to the avoidance of overshadowing and correct orientation. In practice, the large difference in boiler efficiency and air change rate have made this step extremely difficult to analyse. Given the large uncertainties in hot water use and cooking consumption it is not possible to draw any firm conclusions as to whether such a solar contribution exists or not.

The Neath Hill houses had higher winter average internal temperatures than the Pennyland Area 1 houses, hence the large estimate of energy saving in the raw data and from measured house heat losses. These estimates reduce when an assumption of equivalent internal temperatures is imposed, both in correcting the raw data and in the NBSLD model.

Figure 6.25 ESTIMATES OF ENERGY SAVINGS BY DIFFERENT METHODS



68% Confidence range
(95% confidence range approximately double this)

Pennyland 1 - Pennyland 2		useful kWh/yr
Annual space heating analysis	- raw data	1500 \pm 560
	- corrected to end-of-terrace	1400 \pm 400
	- corrected to common temperature	1900 \pm 400
From measured house heat losses		2450 \pm 220
From NBSLD model		2602

Since the Pennyland Area 1 houses had lower internal temperatures than either Neath Hill or Pennyland Area 2, the energy savings from the raw data are on the low side, the benefits of the extra insulation in Pennyland 2 being taken as extra temperature. Correcting the data to a common temperature increases the estimated energy savings as the extra temperature is now expressed as equivalent energy use. This also brings the measured estimate closer to that calculated using the NBSLD model (which approximates to a common internal temperature) and the estimate from the measured house heat losses.

The energy saving produced by this step is fairly important to determine accurately, since it is the one that relates to the benefits of introducing the Danish BR77 regulations in the U.K. There is no way of telling whether the increased internal temperature in Area 2 is useful or not, but for the purposes of cost-effectiveness calculations in the next chapter it has been assumed that they are. There certainly appears to be a higher degree of satisfaction with heating performance in Area 2.

Dual Aspect - Single Aspect		useful kWh/yr
Annual space heating analysis	- raw data	0 \pm 550
	- corrected to end-of-terrace	-90 \pm 350
	- corrected to common temperature	670 \pm 350
From NBSLD model	- Pennyland 1	-20
	- Pennyland 2	9

Here the results are fairly conclusive. Given the designs of the houses used at Pennyland the space heating difference appears to be about zero, in line with the results of the NBSLD model.

The single aspect houses appear to be slightly warmer than the dual aspect ones. Unfortunately, some or all of this difference may be due to the positioning of the external temperature sensors, rather than to a real difference in internal temperatures (see section 4.4.1). If all of the difference were real, and if all of it were useful, then it would be worth about 700 kWh/yr in energy terms.

6.7 Wider Comparisons with Other Houses

The energy savings of both this and the Linford project have been calculated using a sample of 18 houses on the Neath Hill estate (the uninsulated group), to represent 'Brand X', the normal British house. The Neath Hill houses can in no way be described as a deliberate choice of poor quality houses picked to make the Pennyland performance look artificially good. The Neath Hill estate was the show estate of Milton Keynes for 1978 & 79 and was deliberately built and detailed to high standards because of the poor reputation of some of the previous Milton Keynes estates.

However, this sample of 18 houses can hardly be taken to represent the rest of modern U.K. housing without some further comparisons. Two ways of extending the project to wider surveys have been used:-

1. A comparison with annual gas consumptions on four other Milton Keynes estates for the winter of 1975/76.
2. A comparison of boiler gas consumptions with 'McNair's Equation', a simple relation between fuel use, number of occupants, house heat loss and degree days, produced by British Gas.

6.7.1. Other Milton Keynes Data

During the Bradville active solar house project, the question was raised of whether or not the energy use of the occupants was 'normal'. This was very important since the energy output of the active solar system was very dependent on the heating demand, with consequent effects on its cost-effectiveness. The Pennyland project poses the same question as to whether the Neath Hill uninsulated houses can be regarded as 'normal'.

In answer to the Bradville solar house question, and as part of the design studies for the Pennyland project, annual gas and electricity consumptions for 5-person houses on nine Milton Keynes estates were gathered. The results for the four estates with full gas central heating for space and water heating are shown below:-

Estate	Delivered Energy	
	Gas	Electricity
Bradville 1	24348	2189
Fullers Slade	23674	2086
Stantonbury 1	18576	2003
Windmill Hill	22121	2841
Average	22172	2416

Table 6.12

This data was gathered for the period March 1975 - February 1976 (with slight variations due to precise meter reading dates) and in the interests of consumer privacy only average digests were prepared.

The houses in the four-estate sample (about 150 in all) were all built to the 1975 building regulation standards and thus differ from the Neath Hill houses in only requiring 25 mm loft insulation rather than 50 mm.

This would imply an extra energy consumption of about 1500 kWh/yr of delivered energy. Fortunately this amount is almost exactly offset by the fact that the 75/76 weather was slightly warmer than the 81/82 period used for the main Pennyland comparisons by about 100 degree-days. This makes the consumption figures reasonably comparable. The table below shows the Pennyland and Neath Hill figures compared to the 4-estate sample:-

Sample	No. of Houses	DELIVERED ENERGY			
		Gas		Electricity	
		kWh/yr	£/yr*	kWh/yr	£/yr*
M.K. 4-Estate Sample (75/76 Data)	150	22172	253	2416	121
Neath Hill Uninsulated	18	23400	267	Not Measured	
Neath Hill Insulated	14	22480	256	3086	154
Pennyland 1	33	14010	160	2856	143
Pennyland 2	15	11530	131	2598	148

Table 6.13

*Spring 1984 prices

This table clearly reinforces the overall picture of a halving of annual gas consumption across the project, but with little change in annual electricity consumption.

Comparisons have been made between the measured winter internal temperatures in the Bradville solar house and its energy consumption in relation to similar houses in the rest of the estate (see ref.6.10). These would imply quite high internal temperatures in the rest of the estate (17-18°C), though a sample of one is not really much to go on.

6.7.2 McNair's Equation

Another wider comparison that can be made is with a simple empirical equation produced by Peter McNair of British Gas. (ref 6.11)

This aims to estimate annual central heating gas consumption as a function of house fabric heat loss, no. of occupants and degree-days. The formula is based on the analysis of 96 houses over a wide range of types and locations. The equation is similar in form to that used in the statistical analysis in section 6.2.

In fact the equation was developed for similar purposes, to improve the estimates of the differences in energy consumption between houses heated with individual central heating systems and those heated using district heating. It should also be pointed out that the coefficients are subject to the same large statistical ranges as those produced for section 6.2. (see ref. 6.12)

$$\begin{aligned}\text{Annual Heating Gas Consumption} &= 61 + (70.\text{DHL}.\text{DD}/2222) + 59.\text{N} \text{ Therms/yr} \\ &= 204 + (234.\text{DHL}.\text{DD}/2222) + 197.\text{N} \text{ Mean Watts}\end{aligned}$$

where DHL = Design Heat Loss in kW
 DD = No. of degree-days to base 15.5°C
 N = No. of occupants

The design heat losses have been calculated on the basis of the following internal temperatures and air change rates, with a design external temperature of -1°C.

	°C	ac/h
Living/dining room	21	1.5
Kitchen/W.C./Hall	18	2.0
Bedrooms	16	0.5

The resulting average design heat losses for the Pennyland and Neath Hill houses are given below, with the average number of house occupants:-

	DHL kW	No.of occupants
Neath Hill Insulated	5.2	3.4
Pennyland 1	5.1	3.2
Pennyland 2	4.0	3.0

The weather data for the monitored period totalled 2271 degree-days, very close to the 'standard' U.K. value of 2222 used in the equation.

Feeding these values into the equation allows us to compare estate average predicted heating energy consumptions with those actually measured:-

	Annual Boiler Gas Consumption kWh/yr	
	Predicted	Measured
Neath Hill Insulated	18571	20901
Pennyland 1	18080	13166
Pennyland 2	15365	10906

These predicted and measured results are shown on a house-by-house basis in figure 6.26.

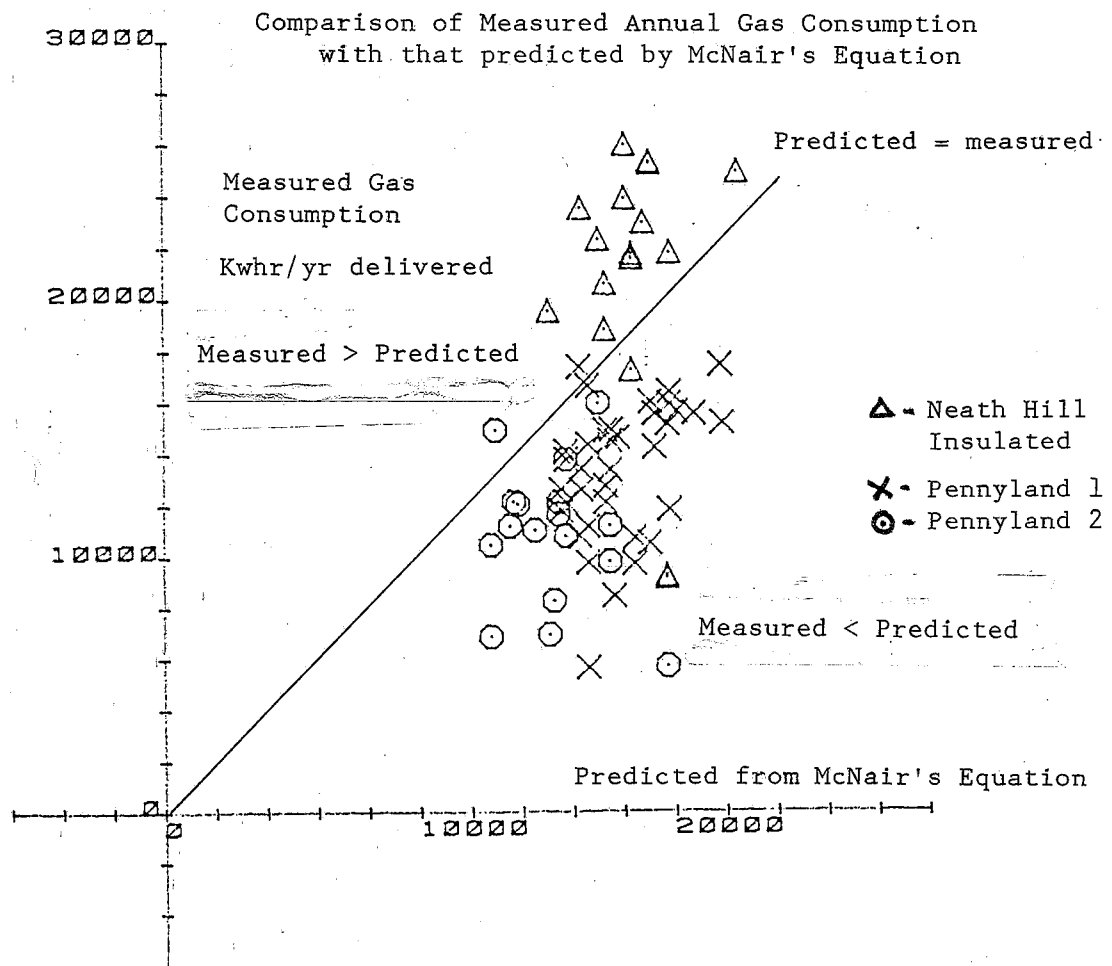
Conclusions

It would appear from these results that the Neath Hill houses are about 20% worse than predicted and the Pennyland houses 20-25% better than predicted.

There are fairly plausible reasons for this:-

1. The Neath Hill houses have possibly slightly higher internal temperatures than other U.K. houses at this insulation level.

Figure 6.26



2. The Neath Hill houses seem to have a higher hot water heating use than average for reasons that are not really clear.
3. The prediction formula makes no allowance for boiler efficiency or house airtightness, hence the good Pennyland performance.

At first sight the Pennyland result seems surprising, since it would seem that there ought to be some law of decreasing returns on energy conservation at high insulation levels. If there is such a law, it does not seem to set in until even higher levels of insulation than Pennyland Area 2 have been reached.

The large measured energy difference between the Neath Hill insulated houses and the Pennyland 1 group, given similar predicted energy consumptions, does indicate that the mere specification of a house heat loss is no real guide to its energy use. This came as somewhat of a surprise to the researchers on this project, though the reasons are now obvious. This does indicate the need for a better way of phrasing Building Regulations in terms of overall energy performance.

6.8 Conclusions on Energy Savings

Although there has been much discussion of the sources of uncertainty and the difficulties in drawing firm conclusions from the project, it should be remembered that overall the Pennyland Area 2 houses consume about a half of the annual gas consumption of the Neath Hill Uninsulated group, or for that matter a large selection of Milton Keynes houses built only a few years previously.

There is no doubt that a substantial energy saving has been achieved. Indeed the basic statistical data indicates a very high level of confidence in both the saving between Neath Hill and Pennyland and between the two halves of the Pennyland estate. In terms of convincingly demonstrating energy savings, this has probably been the most successful housing field trial conducted in the U.K.

There is good evidence, both from the pressure test measurements and annual energy consumptions that the Pennyland houses have a significantly lower ventilation rate than the Neath Hill houses. There have not been enough tests to determine whether there are significant differences between the two halves of the Pennyland estate.

There is a considerable confidence in the savings associated with the use of low thermal capacity boilers. This is supported by the detailed analysis work carried out on the Linford project.

Apart from an apparent increase in effective solar aperture, determined by weekly regressions, there is not much evidence that the Pennyland dual aspect houses are any better at using solar energy than the Neath Hill ones. The solar comparisons originally intended have been clouded both by the basic statistical problem and unforeseen differences such as the large changes in air leakage and boiler efficiency between Neath Hill and Pennyland. The solar answers, such as they are, have largely been produced by adjusting the design computer model using the results of the Linford test house measurements.

Regression analysis suggests that the single aspect houses have a higher solar energy input than the dual aspect ones, in line with their larger south-facing glazing area. This is not reflected in their raw space heating consumptions and it appears that the extra solar input merely offsets the larger heat losses of the single aspect design.

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CHAPTER 7

COST EFFECTIVENESS

- 7.1 Introduction
- 7.2 Detailed Costings
- 7.3 Heating System Savings
- 7.4 Cost Effectiveness
- 7.5 Comparisons with Original Estimates
- 7.6 Cost Effectiveness of Passive Solar Design
- 7.7 Future Possibilities

This chapter brings together the calculated energy savings from the previous chapter and detailed costs for the various house designs to produce overall cost-effectiveness figures and payback times.

7. COST-EFFECTIVENESS

7.1 Introduction

The previous chapter dealt with the analysis of the overall building performance in energy terms alone. In this chapter we introduce the extra dimension of the construction cost of each energy saving measure to be balanced against the fuel saving. By combining these we arrive at the overall cost-effectiveness of each measure as well as the total project savings.

It was originally intended that the extra construction costs would be worked out as part of the buildability study. However, that study concluded that because of the large variance in labour costs from house to house, it would be impossible to discern the small extra construction costs of the conservation measures in practice, for similar statistical reasons as those that apply to the energy savings. Instead detailed costings have been carried out by Davis, Belfield and Everest, a firm of chartered quantity surveyors and authors of Spon's Guide, a standard reference work on building costs.

These costs have been worked out as if the Pennyland houses had been built in the spring of 1984, using normal construction methods, i.e. similar to Neath Hill, rather than using the actual poured concrete method actually used at Pennyland. This has been done to make the cost-effectiveness figures more applicable to current U.K. construction.

In order to get over the difficulty that the Neath Hill houses are a totally different design to the Pennyland one, marginal extra costs have been worked out on the basis of a 'unified' Neath Hill/Pennyland house shell, in the same way as the computed energy savings. Thus for costing purposes, a Neath Hill house has been taken to be the same as a Pennyland dual aspect house, except for minor adjustments to insulation level, thermal mass and window area, where relevant to the intended comparisons.

It has not been possible to get costings of the Pennyland estate layout itself, the extra road and drainage costs (if any) of the passive solar layout. It is very difficult to compare the costs of the Neath Hill and Pennyland estates directly since there are so many factors involved. It is generally conceded that the Neath Hill estate was rather expensive, mainly due to the high level of detailing in the interests of aesthetic appeal. The Pennyland estate, as built using mass production methods, seems to have been rather cheaper than average to construct.

One review of the cost of building houses on the Pennyland estate (ref. 7.1) compared the estate with the average reported to the Building Cost Information Service. The Pennyland figure of £119.70 per square metre of gross floor area, using the actual poured concrete construction technique is significantly less than the national average figure of £164 (December 1978 prices). In fact the Pennyland figure is in the bottom 15% of the range of all reported building costs. Adding in the site costs to give an estate cost, rather than a house cost, gives a total of £149.50 per square metre of gross floor area.

7.2 Detailed Costings

Table 7.1 below shows the total cost of a Pennyland Area 2 dual aspect house, broken down into the main construction components. This sets the context for the small marginal changes in costs of the various conservation measures.

Table 7.1 Total Costs - Pennyland Area 2 Dual Aspect			
	£	m ²	£/m ²
1. Substructure and Ground Floor	2214	44	50.32
2. Upper Floors	1059	43	24.63
3. Staircases	409	-	-
4. Roof	2646	59	44.85
5. External Walls	3268	86	38.00
6. Windows and External Doors	1502	16	93.88
7. Party Walls	560	38	14.73
8. Internal Walls	1058	69	15.33
9. Internal Doors	1006	-	-
10. Mechanical Services	3332	-	-
11. Electrical Services	943	-	-
12. Sundry Items	1500	-	-
	19497		

One point to note in this table is that there is a considerable difference in cost per square metre between insulated walls and windows. This amounts to about £50-60/m². This is a major cost difference that is important in assessing the cost-effectiveness of passive solar measures.

Table 7.2 below sets out the marginal costs of the energy saving measures for the Neath Hill/Pennyland house shell in its dual aspect form, progressing from the Neath Hill uninsulated level (1976 Building Regulation standards) up to the Pennyland Area 2 level (approximately Danish BR77 standards).

Table 7.2 Marginal Extra Costs

Item	Cost £	Area m ²	Unit ² Cost £/m ²
Neath Hill - Cavity fill	224	81	2.80
Neath Hill - Pennyland 1			
- Loft (50 mm - 80 mm)	25	45	0.56
-- Thermal Mass	93	193	0.48
Pennyland 1 - Pennyland 2			
- Loft (80 mm - 140 mm)	45	45	1.00
- Wall (50 mm - 100 mm)	81	81	1.00
- Floor Edge	39	44	0.89
- Windows (Single - Double)	0	12	0.00
Neath Hill Uninsulated - Pennyland 2 Total	507		

This table shows that the extra construction costs represent only a about 2.5% of the total house construction cost.

There are many comments that can be made about the contents of this table:-

Wall insulation

Two insulation steps have been included, the first from an unfilled cavity to 50 mm cavity insulation, the second from 50 mm to 100 mm including a widening of the cavity.

The first step has been costed at £2.80/m². This is for the insertion of 50 mm fibreglass batt insulation into a cavity. A large proportion of the cost is simply that of fixing the insulation in place. The second step to 100 mm thickness has been costed at only £1.00/m². This considerably lower price just includes the extra material costs plus the costs of increasing the cavity width (extra roof tiles, wider cavity closures, etc.), since the actual fixing costs are likely to be about the same. This tends to make this extra insulation rather more cost-effective than would appear at first sight.

At Neath Hill the cavity was filled with 50 mm urea formaldehyde foam insulation. Although a completely different technique, it unlikely that the costs are significantly different.

Loft Insulation

Again two steps of insulation have been carried out. The first, from 50 mm to 80 mm thickness is costed at £0.56/m² and the second, from 80 mm to 140 mm costs £1.00/m².

Floor Insulation

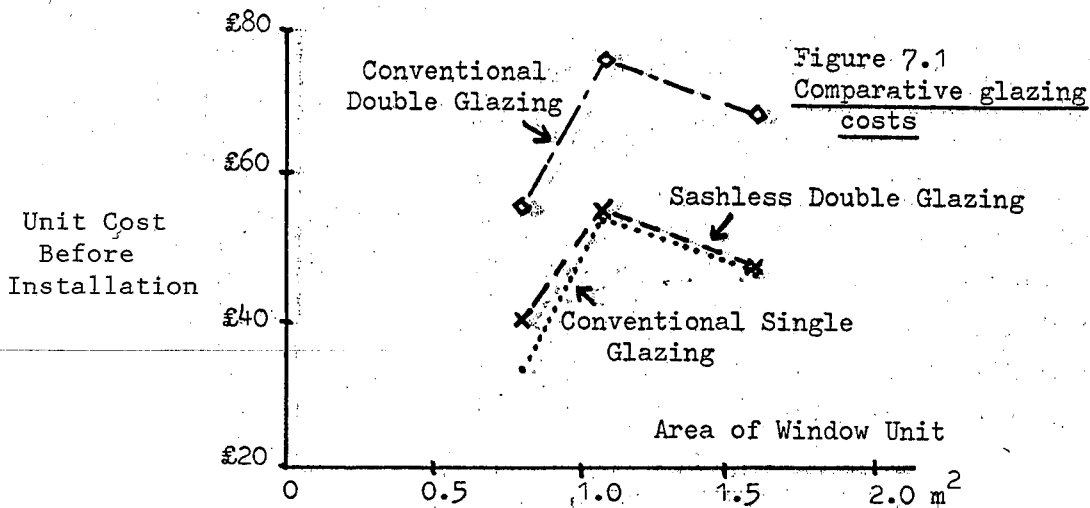
This has been largely taken to be the cost of the edge insulating material and has been taken as a total cost of £39 for a dual aspect end of terrace house and £42 for a single aspect one.

Double Glazing

It may seem quite extraordinary that the Sashless double glazing should cost no more than conventional single glazing, indeed the original costings for the project suggested that it was £9/m² more expensive. The costings by Davis, Belfield and Everest show almost no cost difference.

The basic reason is the substitution of thicker glass for complex and expensive framing in conventional windows. The Sashless window thus has less woodwork and ironmongery than a normal window. The price differential is to a certain extent dependent on the size and complexity of the window, but price comparisons for three typical sizes of window, as shown in figure 7.1, only show a significant price difference for the very smallest area units. Conventional double glazing is about £22/m² more expensive.

The Sashless windows do have certain defects in use, such as rather flimsy plastic catches and a tendency to scratch, but this has to be weighed against the considerable cost saving of about £250/house over conventional double glazing.



Thermal Mass

The method of wall construction at Pennyland was rather unusual, with the inner skin being of in-situ cast concrete. This method is rather difficult to cost accurately, since a large proportion of the costs are in the making of the concrete shuttering. Thus for one-off construction, the method tends to be rather expensive but for large scale work, such as at Pennyland, can be cheaper than conventional building methods.

Since the purpose of the present exercise is to try to arrive at cost-effectiveness conclusions applicable to normal current U.K. practice, costings have been done on the basis of normal brick-and-block construction, as at Neath Hill and Linford. In fact the contractor, John Mowlem, did submit two tenders for the Pennyland estate, one based on conventional construction, and another, cheaper, one using the poured concrete construction.

The specification for the estate required dense concrete internal construction to provide the thermal mass for the passive solar design. In the actual Pennyland construction, this was achieved by using a normal medium-weight concrete mix for the poured inner skin, rather than Mowlem's normal lightweight mix containing a considerable proportion of pulverised fuel ash. The Linford houses and the method costed here, used dense concrete blocks rather than normal lightweight concrete ones.

The thermal mass costs have been surprisingly hard to pin down. The problem seems to be that the cost difference per square metre is very small. It has been taken to be only £0.48/ m^2 , but most of this difference is in labour cost, builders demanding a higher rate to work with the heavier building blocks. This labour cost is subject to a rather high degree of uncertainty and the true cost could be anywhere between zero and £1.00/ m^2 .

This rather uncertain cost is then multiplied by rather a large square metreage, there being almost 200 m² of partition wall, party wall and inner leaf of external wall to consider. The thermal mass costs have thus been taken as £93 for a dual aspect end-of-terrace house.

As well as the items in Table 7.2, there are three other cost items that have to be looked at, the low thermal capacity gas boiler, the costs of increased airtightness and the difference in construction costs between dual aspect and single aspect houses.

Gas Boiler

The Pennyland houses were fitted with a low thermal capacity boiler with a balanced flue. The Neath Hill houses had a conventional heavyweight boiler with a flue extending through the roof. The cost difference between these options has been taken to be zero, though in practice the balanced flue arrangement may be up to £100 cheaper than the conventional flue.

Air-tightness

This is something that seems almost impossible to cost. The good airtightness of the Pennyland houses has been taken to cost essentially nothing, though it is a consequence of the poured concrete construction, the careful design incorporating draught lobbies and the well sealed windows.

Single Aspect - Dual Aspect Costs

The detailed costings of the extra energy saving measures has brought to light large cost differences between the single and dual aspect house designs. The dual aspect deep plan house is perhaps the more normal design as regards U.K. housing, but the Neath Hill estate also has both deep plan and shallow plan houses (see Appendix 3).

The shallow plan houses were originally introduced at Pennyland for aesthetic reasons, though passive solar considerations heavily influenced the design as built.

If the main reason for using the shallow plan design had been to allow the extra south-facing glazing, then most of the extra construction costs should be seen as passive solar ones. A Pennyland Area 2 single aspect house costs an estimated £20,998 and a dual aspect one £19,497, a difference of about £1,500. The detailed costings are given in Appendix 1 but summarised in Table 7.3 below.

Table 7.3 Single Aspect and Dual Aspect Costs
(End of Terrace House - Area 2 Insulation Level)

	Dual	Single	Difference
External Walls	3268	3382	114
Windows and Doors	1502	1887	385
Party Walls	560	442	-128
Roof	2646	2353	-293
Internal Walls	1058	1378	320
Internal Doors	1006	1386	380
Staircase	409	643	234
Meter Cupboard & Porch	-	500	500

It is not fair to ascribe all these cost differences as being essential to the difference in design of a dual aspect deep plan house and a single aspect shallow plan one. The first three items, though, seem unavoidable.

The single aspect house shell has 7 m^2 more external wall and window area and 8 m^2 less party wall area (see figure 7.2). If there were no increase in window area between single and dual aspect designs then the costs would run:-

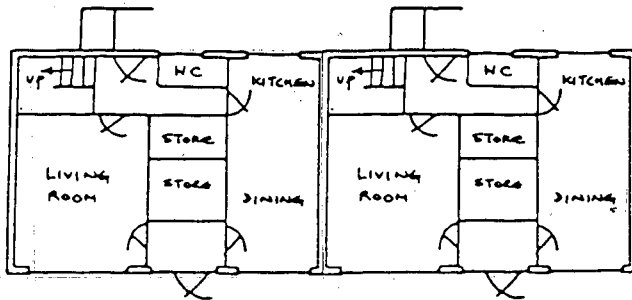
Add 7 m^2 external wall area at $\text{£}38/\text{m}^2$	$\text{£}266$
Less 8 m^2 party wall area at $\text{£}14.73/\text{m}^2$	$-\text{£}128$
	<hr/> $\text{£}138$

The single aspect house shell does have 4 m^2 more window area in practice:-

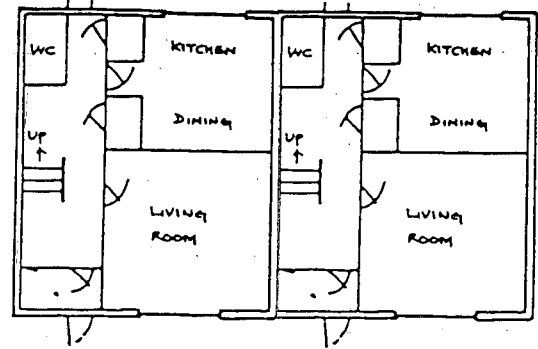
Replace 4 m^2 wall area at $\text{£}38/\text{m}^2$ with double glazed window at $\text{£}94/\text{m}^2$	$\text{£}224$
--	---------------

A shallow plan house is intrinsically more expensive to build than a deep plan one because of the difference in price of external walls and party walls, the costs of which are shared with the adjoining house anyway. The shape change and the increased glazing area of the Pennyland single aspect houses means that they are bound to be at least $\text{£}362$ more expensive to build than the dual aspect design.

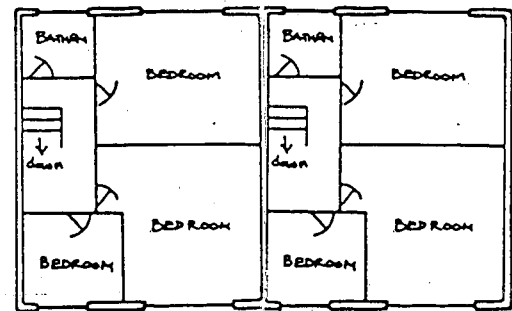
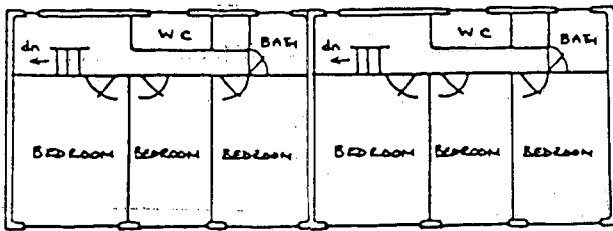
The other extra costs (staircase, meter cupboard, etc.) making up the rest of the actual $\text{£}1500$ difference are peculiar to the particular choice of internal arrangements in these houses and are not generalisable to other designs.



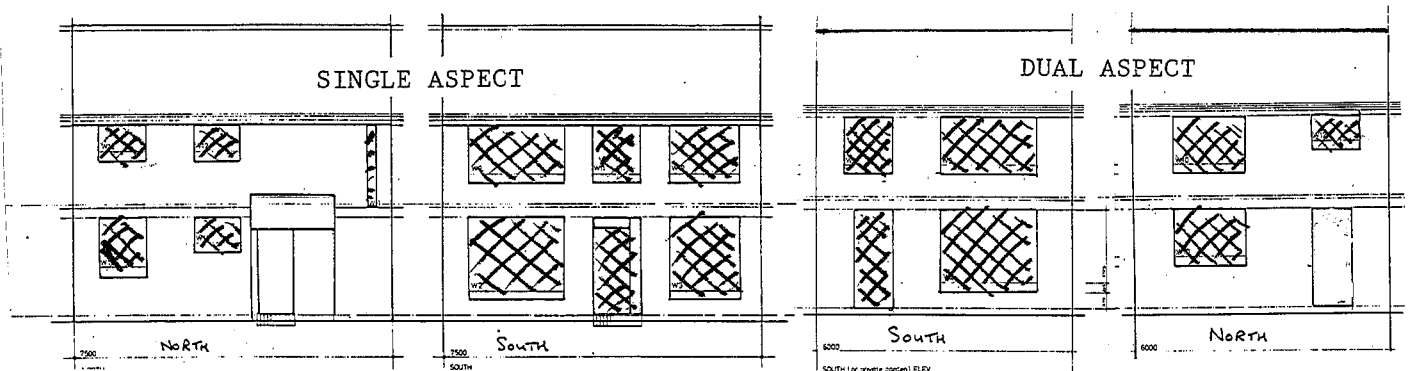
Single Aspect Design



Dual Aspect Design



The single aspect design as built requires more external wall area/unit floor area than the dual aspect type in a semi-detached or terrace arrangement. It also has more internal doors.



The single aspect design has 4 m^2 more total window area than the dual aspect design.

Figure 7.2

COST DIFFERENCES BETWEEN SINGLE AND DUAL ASPECT HOUSE DESIGNS.

7.3 Heating System Savings

The extra costs of insulation can, to a small extent, be offset by the reduced costs of the heating system. It was difficult to explore this at the design stage, given the uncertainties in sizing systems for low energy houses. The measurements on the Linford houses and especially the performance through the cold weather of December 1981, have given considerable confidence in this area.

The system savings split into two different areas, savings due to reduced radiator sizes and those due to reduced boiler sizes. Since radiators tend to come in a wide range of sizes and there are a large number in a house, radiator costs tend to be a fairly smooth function of the fabric heat loss of a house.

Boilers, on the other hand, tend to come in a restricted range of sizes, with a step in output power of about 4 kW between them. Thus in comparing two house designs, boiler cost savings (around £60 per 4 kW step) may suddenly appear at rather arbitrary points.

A fairly detailed costing of radiators and boilers was carried out for the Linford houses. The result of this was that for every kW reduction in design heat loss for a house, there would be on average £15 saving in radiator costs and on average, over a wide range of house heat loss values, an extra £15 in reduced boiler costs.

This figure of £30/kW has been used to offset the Pennyland insulation costs, the overall effect being to save about 10%.

It is perhaps worth noting that there may be an extra 'thermal mass' cost here as well, in the shape of an increased heating system size to cope with notions of a longer warm-up time. This could amount to a 20% oversizing or an extra cost of about £30.

7.4 Cost-Effectiveness

By bringing together the extra construction costs, the heating system savings and the annual fuel cost savings, it is now possible to assess the payback times of the various measures.

Two separate sets of energy savings have been used, the refined measured results from Table 6.4 which are the best estimates of the measured energy savings, taking increased internal temperatures to be useful, and the computed results from Table 6.11 which have been produced by the design computer model updated in the light of experimental results. A fuel cost of 33.5p/therm has been used, equivalent to 1.14p/delivered kWh of gas.

Table 7.4 Cost-Effectiveness from Computed Energy Savings

	Delivered Energy Saving		Gross Heating Extra System Cost Saving		Net Extra Cost	Payback Time
	kWh/yr	£/yr	£	£	£	Yrs.
NEATH HILL UNINSULATED						
50 mm wall insulation	2642	30.1	224	26	198	6.6
NEATH HILL INSULATED						
Roof ins. 50-75 mm	485	5.5	25	5	20	3.6
Improved Boiler	2862	32.6	0	0	0	0
Add thermal mass	-695	-6.1	93	0	93	Inf.
Reduce vent. rate	1319	15.0	0	0	0	0
Marg. Solar Gains	283	3.2	0	0	0	0
PENNYLAND AREA 1						
Roof ins. 75-150 mm	661	7.5	45	5	40	5.3
Wall ins. 50-100 mm	1351	15.4	81	13	68	4.4
Double Glaze	729	8.3	0	13	-13	0
Floor insulation	348	4.0	39	5	34	8.5
PENNYLAND AREA 2						
OVERALL N.H.U. to PENNYLAND AREA 2	10016	114.2	507	67	440	3.9
N.H.I. to PENNYLAND 1	4254	48.5	118	5	113	2.3
PENNYLAND 1 to PENNYLAND 2	3120	35.2	165	36	129	3.7

Table 7.5

COST-BENEFIT OF MEASURES FROM REFINED MEASURED RESULTS

	Useful Energy Saving kWh/yr	Delivered Energy Saving kWh/yr	Value £/yr	Gross Extra Cost £	Heating System Saving £	Net Extra Cost £	Payback time yrs.
NEATH HILL UNINSULATED							
50mm foam cavity ins.	1850	2500	28.5	224	26	198	6.9
NEATH HILL INSULATED							
Improved Boiler	-	3400	38.8	0	0	0	0
Roof ins., Reduced vent. Solar & Mass	1500	2027	23.1	118	5	113	4.9
PENNYLAND 1 Insulation	1900	2235	25.5	165	36	129	5.1
PENNYLAND 2							
Overall N.H.U. to PENNYLAND 2	-	10162	115.8	507	67	440	3.8
N.H.I. to PENNYLAND 1	-	5427	61.9	118	5	113	1.8

These two tables tell essentially the same story, though one is limited by the credibility of the computer model and the other by the statistical problems of determining the energy savings.

Compared to the uninsulated Neath Hill houses, the Pennyland Area 2 houses show an overall saving of about £115/yr, with a payback time of about four years. The improvement in insulation standard between the two halves of the Pennyland estate shows an energy saving of about £30/year with a similar time.

The overall cost-effectiveness is greatly assisted by the large boiler energy savings and those due to the Sashless double glazing, which have both been achieved with no extra cost. Indeed, because the double glazing allows a small reduction in heating system size, it actually has a negative marginal cost.

Reducing the air infiltration rate produces about 14% of the total project energy savings, for a cost which is difficult to determine, but probably close to zero.

Increasing the wall insulation is very cost-effective, both for the step from zero to 50 mm thickness and for the increase to 100 mm thickness. Both have payback times of about 5-6 years. The good performance of the 50 mm-100 mm step is due to the fact that the basic fixing costs of the insulation are estimated to be about the same as for the initial step. The lower energy savings of the second step are thus balanced against just the marginal cost of the material and the costs of widening the cavity to 100 mm thickness.

Increasing the roof insulation thickness from 50 mm to 80 mm (75 mm in the computer description) is very cost-effective, with a payback time of under four years. The second step from 80 mm to 140 mm (75 mm to 150 mm in the computer model) is not so cost-effective, with a law of decreasing returns setting in. Insulation thicknesses of over 150 mm may be cost-effective if payback times of greater than 20 years can be accepted.

Floor edge insulation, with a payback time of over eight years does not seem at first sight a very good investment. However, the Linford project measured far higher heat losses than expected, not apparently due to defective floor insulation. It also revealed a serious lack of actual floor heat loss measurements. It is thus quite possible that the true payback period of the floor edge insulation is under five years.

Floor edge insulation is also desirable to prevent condensation problems due to the cold bridge under the insulated wall. This has been a problem on another Milton Keynes estate (Beanhill) and edge insulation has had to be retrofitted as a solution. It is possible that full underfloor insulation would be cost-effective for future low energy houses.

The passive solar savings in Table 7.4 have just been taken to be those due to the avoidance of overshadowing and correct orientation of a dual aspect house (i.e. Neath Hill to Pennyland 1 dual aspect). As such they have been taken to have zero cost. Although these savings only amount to 3% of the total project savings, they are potentially highly cost-effective.

The extra thermal mass of the Pennyland houses has not been taken to be a passive solar item, since it does not in practice seem to have been necessary for the passive solar design. Indeed, it seems to have increased the construction cost of the houses and increased their energy consumption without noticeably affecting peak summer temperatures.

The full cost-effectiveness of the passive solar design will be discussed in section 7.6.

7.5 Comparison with Original Estimates

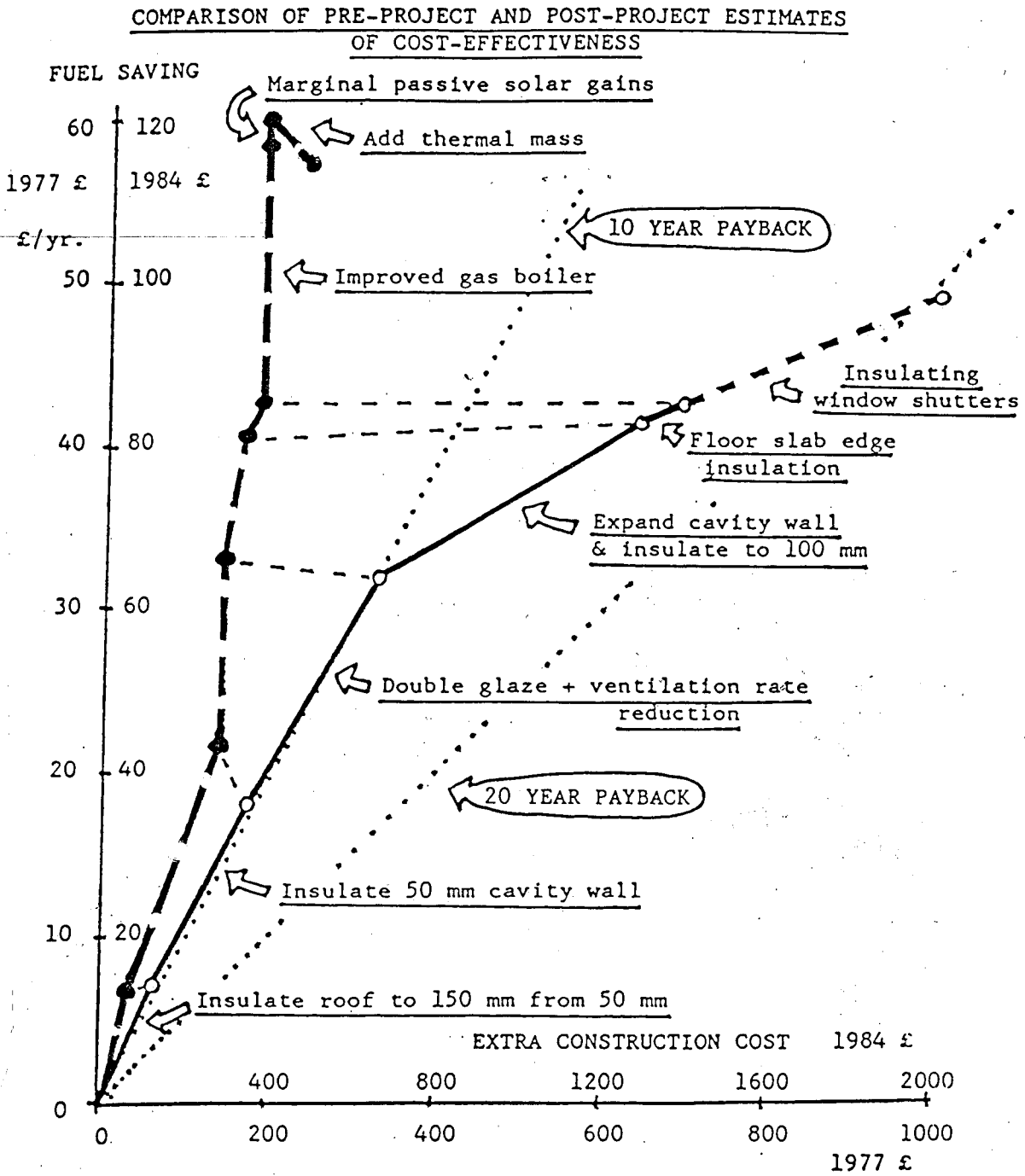
It is interesting to compare the computed cost-effectiveness of the various measures with that estimated at the outset of the project (see figure 2.3). Conveniently inflation has reduced the value of the pound by almost exactly a factor of two between 1977 and 1984, allowing the pre-project and post-project estimates to be plotted fairly simply on one graph (see figure 7.3).

While the energy savings for individual measures are similar for both plots, the costs of insulation at the higher levels have fallen dramatically since 1977. The low costs of the double glazing and the added bonus of a large boiler efficiency saving for no extra cost have dramatically improved the overall payback time of the package of measures.

The original design aim was for a package of measures that would pay for itself in 10-15 years. The project results are nearer five years. This is four times better than the Treasury 5% discount rate criterion used for energy projects (building power stations, closing coal mines, etc.) When given a 60 year investment lifetime (i.e. the life expectancy of the house), this is equivalent to a payback time of 18.9 years. Considerations such as future increases in real gas price, which are highly likely in the near future, would make the energy conservation investment even more attractive.

Some items have not been cost-effective. The additional thermal mass of the Pennyland design has a high cost for no visible benefit. The insulating window shutters fitted to some houses and included in the original cost-effectiveness calculations are unlikely to have been used enough to justify their installation.

Figure 7.3



7.6 Cost-effectiveness of Passive Solar Design

This is an extremely difficult topic, since anything that changes the appearance of a house or an estate layout becomes rapidly confused with changes made for purely aesthetic reasons, changes that may affect the selling price of a house or indeed whether a whole estate becomes a slum or a garden suburb. It does not seem to be possible to produce hard cost-effectiveness figures for changes in house shape or layout in the same way that can be done for the more 'invisible' energy savings measures such as insulation and boiler efficiency.

In this section, therefore, we will first look at the computed passive solar energy savings, mainly derived from Linford test house results, and then at the residents' preferences as regards house design and estate layout.

7.6.1. Computed energy savings.

The passive solar variants have been broken down into five design steps as shown in figure 7.4. These steps have been given a list of potential benefits and disbenefits, a possible cost and an overall rating.

The steps used are as follows starting from a Neath Hill type overshadowed and poorly oriented true dual aspect house, i.e. with the same area of glazing on both facades:-

1. Face south, avoid overshadowing
2. Concentrate glazing on south side without changing house shape. South-facing glazing area 7.4 m^2 , north-facing area 4.7 m^2 .
3. Add thermal mass to give heavyweight construction. This gives as Pennyland dual aspect type house.
4. Rearrange house to shallow plan. Concentrate the glazing on the south side without increasing the total area.
5. Increase the south-facing glazing area to 13.6 m^2 , north-facing glazed area 3.9 m^2 . This is a Pennyland single aspect house type

Step 1 - Face south, avoid overshadowing

This is likely to produce an energy saving of around 150-250 kWh/yr, depending on how bad the overshadowing really is (see figure 6.10), and the level of window clutter. A southerly orientation will give sunny south-facing rooms but means that north-facing rooms will be darker. Facing the house south is also the best orientation from the point of view of summer overheating. East and west-facing rooms will tend to overheat far more.

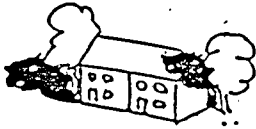
This step will produce a constraint on the estate layout, though the Pennyland estate has shown that this need not be a great problem. The cost of this step is almost impossible to estimate, but could easily be zero.

Given that the sun in the living rooms has been greatly appreciated by the occupants, this step can be rated quite highly.

PASSIVE SOLAR DESIGN STEPS

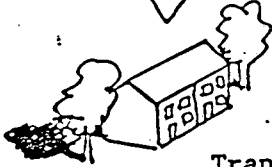
Figure 7.4

NEATH HILL

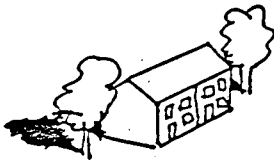


'Normal' deep-plan house, overshadowed & randomly oriented. 12 m² total window area, net curtains.

Face south, avoid overshadowing

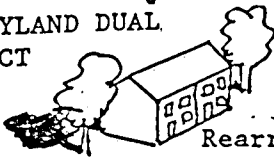


Transfer some glazing from north to south facades without increasing total area or changing house shape.

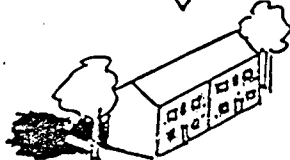


Add thermal mass - medium weight to heavyweight construction

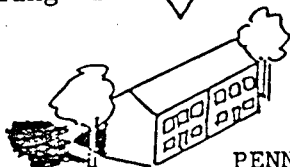
PENNYLAND DUAL ASPECT



Rearrange house to shallow plan. Concentrate glazing on south side without increasing total area.



Increase south-facing glazing area



PENNYLAND SINGLE ASPECT

BENEFITS: Energy saving ≈ 200 kWh/yr (useful)
Sunny south-facing rooms
Cost probably zero

DISBENEFIT: Constrains estate layout

RATING: Good, likely to be popular

BENEFITS: Energy saving 50-80 kWh/yr per m² of glazing transferred.
Sunny south-facing rooms
Cost probably zero

DISBENEFIT: Darker north-facing rooms

RATING: Good, sunny rooms likely to be popular.

BENEFITS: Reduced summer overheating
Good soundproofing

DISBENEFITS: Poorer wall U-values
3-700 kWh/yr extra space heating
Extra construction cost \approx £100

RATING: Unnecessary, medium weight construction should be adequate.

BENEFITS: Most rooms are sunny
Mixture of deep and shallow plan houses adds variety to estate.

DISBENEFITS: Featureless north facade
Extra cost due to increased ratio of external to party wall approximately £150

RATING: Moderate, not cost-effective but may be more popular design.

BENEFITS: South-facing rooms sunnier.

DISBENEFITS: Privacy problems
Risk of overheating
Increased energy consumption with single glazing.
Extra costs due to £60/m² difference between windows and insulated wall

RATING: Poor

Step 2 - Concentrate glazing on the south side

This will produce a useful energy saving of between 50 and 80 kWh/yr for every square metre of glazing transferred from the north to the south facade. As is described in the Linford report, most marginal passive solar savings are dependent on the length of the heating season, whether or not it extends into the sunnier spring and autumn weather. Consequently the higher figure of 80 kWh/yr. is more applicable to the Pennyland Area 1 houses and the figure of 50 kWh/yr to Area 2.

Since the total heat loss of the house does not change by this process, it does not matter whether the glazing transferred is single or double. Given that the amount of solar radiation falling on the south-facing vertical surface over a typical heating season is only about 300 kWh/m²/yr, this step can perhaps be interpreted as 'collecting' solar energy with an efficiency of between 15 and 25%.

Transferring glazing to the south side will make the north-facing rooms darker, which may incur extra electric lighting energy consumption, though this project has failed to produce any answers on this matter.

If only small areas of glazing are transferred, then the extra construction cost involved may be close to zero, making this a very cost-effective way of saving a relatively small amount of energy.

Given that the sunny south-facing rooms are likely to be popular, this step can be rated quite highly.

Step 3 - Add thermal mass

This has the effect of reducing peak summer temperatures and improving the soundproofing of the houses. The survey of peak summer temperatures at Pennyland and Neath Hill failed to find any significant difference between the Pennyland Area 1 houses with heavyweight construction and the Neath Hill houses built with normal medium weight blockwork. In neither case were the internal temperatures excessive. It would thus seem that the extra thermal mass is not really needed.

The dense concrete construction used at Pennyland and Linford does mean that the wall U-values are slightly higher than they would be with medium weight construction. These increased heat losses can mean an extra space heating demand of 300-700 kWh/yr (the effect is highest at poorer wall insulation levels). Thus if thermal mass is to be incorporated into the structure it should not be put in the inner leaf of the external walls.

The dense concrete construction, costed as dense concrete blocks, as used at Linford, increases the construction cost of a Pennyland house by about £100, though this is subject to considerable uncertainty.

On balance, it would seem that as long as south-facing glazing areas are not excessive, the use of heavyweight construction is not necessary. Medium weight blockwork should be sufficient.

Measurements at the Linford test house showed that a concrete ground floor slab, once covered with floor tiles or carpet, was not a significant contribution to the thermal mass of a house from a solar point of view.

Step 4 - Rearrange to shallow plan, concentrate glazing on south side

This step places most of the living rooms on the south side of the house. In doing so it does make the north façade into somewhat of a bare brick wall that may not look particularly attractive. It also means that the north facing rooms and hallway₂ are rather dark, since the Pennyland single aspect houses had 0.8 m^2 less north-facing glazing than the dual aspect type.

Making the house shell more shallow increases the surface area of a terrace or semi-detached pair (but not a detached house). This increased surface area implies an increased energy consumption. However, this is almost exactly offset by the transfer of 0.8 m^2 of glazing from the north to the south side, giving the single and dual aspect semi-detached houses almost exactly the same theoretical energy consumption.

The change in house shape does mean an increase in construction cost, as described in section 7.3 and Appendix 1. Of this increase, it is fair to ascribe about £150 as an unavoidable cost of the design change.

Given the extra construction cost, for almost no energy saving, this step cannot be rated as cost-effective from an energy point of view. The mixture of single and dual aspect houses has, though, made a much more attractive overall housing scheme.

Step 5 - Increase south-facing window area

There seems little energy benefit in increasing the south-facing window area excessively. Figure 7.5 shows computed plots of space heating demand versus south-facing window area for a single aspect house design at both the Area 1 and Area 2 insulation levels.

This diagram clearly shows that for a single glazed window the energy optimum is as small as possible. For a double glazed window, though, the house space heating consumption is largely independent of the south-facing window area.

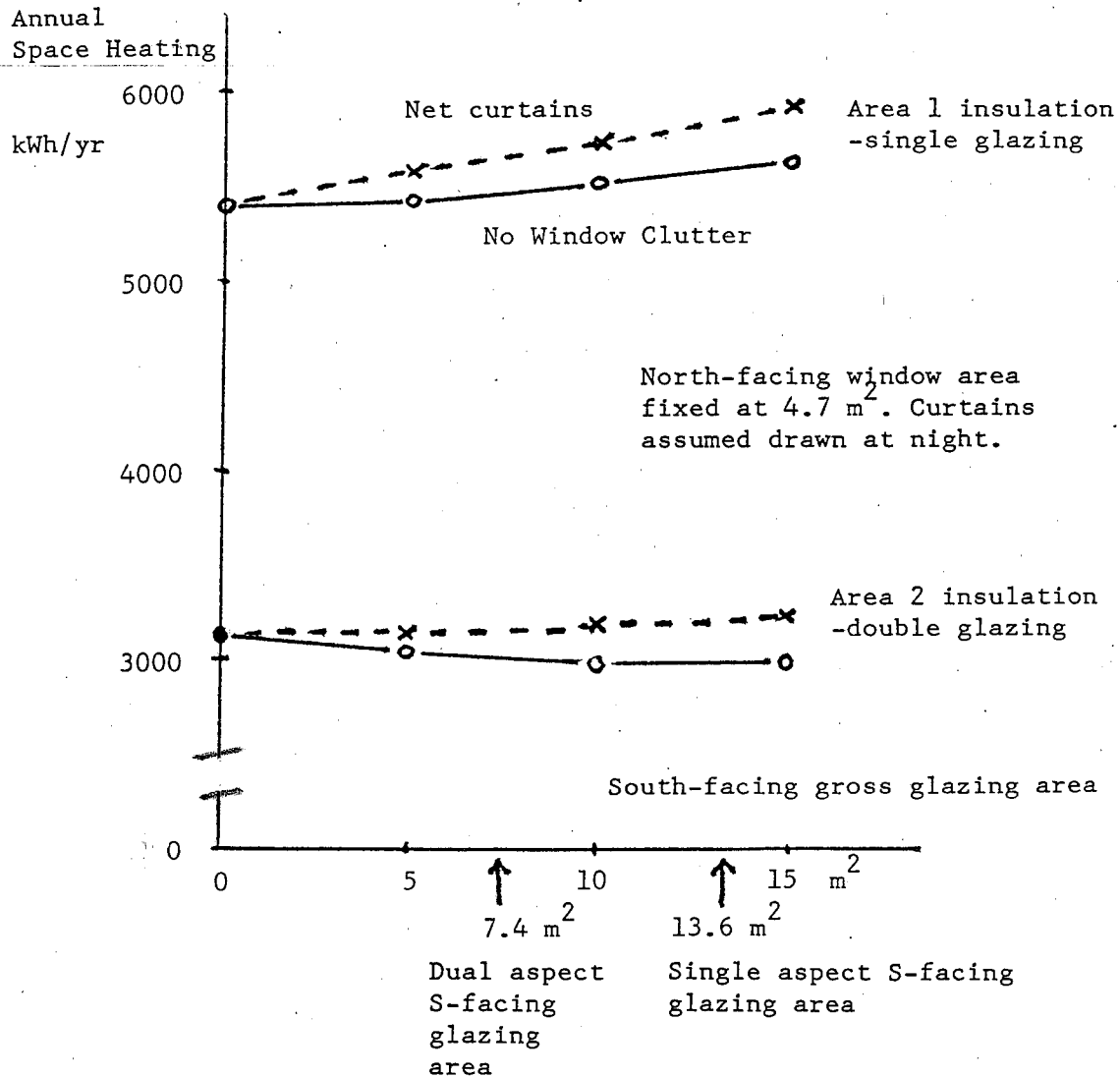
Increasing the window area increases summer overheating problems and privacy problems. The actual choice of window area, however, must be an aesthetic one. Single glazed and sashless double glazed windows are £50-£60/ m^2 more expensive than insulated wall (£80/ m^2 for conventional double glazing). Thus in all cases, the cost-effective optimum area is close to zero.

The only firm conclusion that we can make from this list is that as long as the south-facing window area is kept limited, the use of dense concrete construction is an unnecessary expense.

Steps 1 & 2 appear to be more cost-effective than 4 & 5, but in practice the costs involved are trifling compared to those made for purely aesthetic purposes, such as the landscape mounds at Pennyland or the wooden balconies and porches at Neath Hill.

Figure 7.5

POST-PROJECT COMPUTED SPACE HEATING
CONSUMPTION AS A FUNCTION OF SOUTH-FACING
WINDOW AREA - SINGLE ASPECT TYPE HOUSE



In houses at the Area 1 insulation level south-facing single glazing is a net energy loser - the energy optimum area is as small as possible.

At the Area 2 level space heating consumption is almost independent of S-facing window area. Excessive levels will lead to summer overheating without any energy savings.

The energy savings (less than £10/yr) are also small compared with the more drastic considerations of layout and built form that were considered in the social survey.

7.6.2. Residents' preferences

This chapter may sound in parts like suggesting that residents must live in the most energy cost-effective house whether they like it or not. It is therefore important to weigh up their opinions on the house designs from the social survey.

The residents generally:-

- a) liked having sun in the living rooms
- b) were concerned about privacy and space
- c) liked individuality in house design
- d) were not terribly concerned about minor differences in fuel consumption between different house designs.

75% of Pennyland residents interviewed liked the south-facing windows and large ones were preferred. 87% thought that the amount of sun in the living room was about right (see figure 7.6).

43% of residents felt that there was too little privacy at the back (south) of the house and 22% felt that there was too little on the north side, though the majority thought it about right (see figure 7.7). A large number of people suggested that better fencing would improve the privacy problem (the estate was only provided with token wire fencing to keep costs down). Only six residents thought that the garden mounding provided privacy and most thought it a nuisance.

As far as noise problems were concerned most people liked the solid construction and the double glazing.

Occupants were asked to compare four possible estate layouts, as shown in figure 7.8:-

- a) The Pennyland estate as built
- b) A layout of semi-detached houses which they were told would cost £15/yr more to heat.
- c) A terrace layout which they were told would cost £15/yr less to heat. (It would also have been cheaper to build).
- d) A Neath Hill style courtyard layout which they were told would cost £30/yr more to heat because of lack of solar gains.

The comparison was done in two parts. In the first, the first three layouts were compared. In the second, the residents were asked to compare the Pennyland layout with the Neath Hill scheme.

The results of the first comparison were that the Pennyland and semi-detached layouts were rated equally popular while 94% disliked the terrace layout most of all. The fuel savings between the layouts were not seen as important.

In the comparison of the Pennyland and Neath Hill arrangements, over 95% preferred Pennyland. The main criticism of the Neath Hill style layout was much the same as for the terrace layout. It was 'all the same', 'boring', 'just arranged in straight lines'. It was felt that the Neath Hill arrangement gave no improvement in privacy and just cut down the sun in the living rooms.

RESIDENTS' PREFERENCES

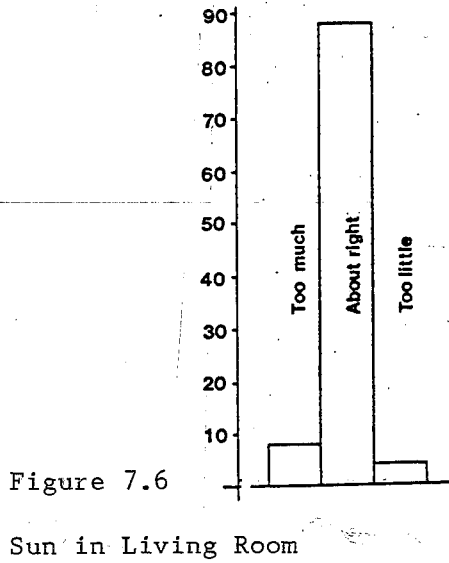
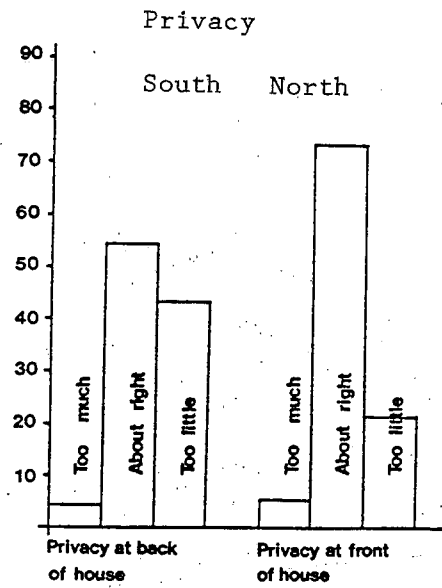
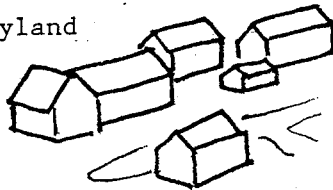


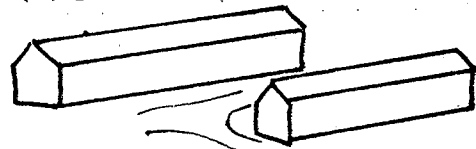
Figure 7.7



(a) Pennyland

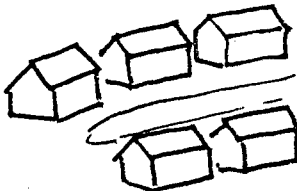


(c) Slab Terrace



POPULAR \longleftrightarrow LESS POPULAR

(b) Semi-detached



(d) Neath Hill courtyard style

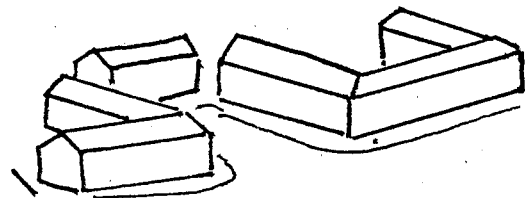


Figure 7.8 Social Survey popularity of estate layouts

Thus it would seem that the most energy cost-effective house form, the slab terrace, which is cheapest to build and to heat, is by far the most unpopular. This may be influenced by the proximity to other estates where great attention has been paid to making every house indistinguishable from its neighbours (in the name of architectural 'purity').

This means that we cannot assume that the most energy cost-effective house design is automatically the 'best' house design. Every house is someone's home and this has to be taken into account. A private developer has to consider the 'kerb appeal' of a house (whether or not a potential buyer bothers to get out of their car to look at it) and considerations of variety and individuality will affect the selling price.

From a local authority point of view it can make the difference between a 'hard to let' estate that may degenerate into a slum and one that becomes a 'garden suburb'. Tenant satisfaction and low maintenance costs are also very important. Most of the Pennyland residents chose to move there because they liked the well designed estate and the traditional looking appearance and construction.

7.6.3. Choice of south-facing window area

What is the best area of south-facing glazing? Unfortunately this project has not produced any clear answers to this question.

If the glazing area is too big then there are likely to be overheating and privacy problems, and with single glazing, possibly problems of cold bedrooms in winter without upstairs heating.

A house with small windows is definitely cheaper to build, since windows cost at least £50/m² more than insulated walls. Residents seem to prefer fairly large windows and considerations of internal daylighting only become important when the window area is reduced below about 10% of the wall area (ref. 7.4).

Perhaps the best answer is that in Area 2 with double glazing, the window areas are about right. In Area 1, with single glazing, either the upstairs window areas should be reduced or extra heating should be installed to maintain comfort conditions (the Area 1 houses just meet the current 12% or perimeter wall area window limit for single glazing).

7.7 Future Possibilities

As a result of the Pennyland and Linford projects three possible areas for further cost-effective improvements have become apparent:-

1. Further increases in boiler efficiency
2. Extra heating system insulation
3. Extra fabric insulation.

Figure 7.3 shows the the Pennyland house design has not reached the limits of cost-effective energy saving. This would happen when the return on the last energy saving measure applied to the house was at the limit of financial acceptability. This perhaps could be taken to be the 5% Treasury discount rate criterion, or, more simply a 20 year marginal payback time.

Increases in Boiler Efficiency

Further increases in boiler efficiency could result from two improvements, the introduction of condensing boilers, which are just becoming available in this country, and the replacement of pilot lights with electronic ignition. Condensing boilers can achieve marginal heating efficiencies of 95% or more by extracting the latent heat of evaporation of the water vapour in the flue gas. The use of electronic ignition would dramatically cut the boiler standing losses that make up over 20% of the annual as consumption of a Pennyland Area 2 house (see figure 6.22), though care would have to be taken not to substitute an electric standing loss for a gas one.

These increases in boiler efficiency could easily lead to further energy savings of £20/yr for little extra cost.

Extra Heating System Insulation

The Linford project identified the high level of heat losses from the hot water cylinder. Although some of these losses can be taken as useful free heat, it is likely that a halving of the losses from 3 kWh/day to 1.5 kWh/day with extra lagging would save about 300 kWh/yr of delivered energy for an extra cost of about £10. This would thus have a payback time of about three years.

Extra Fabric Insulation

The payback time of increasing the wall insulation from 50 mm to 100 mm was about five years. Given the same basis for costing, the payback time of the next step, from 100 mm to 150 mm is likely to be a factor of three worse, say around 15 years. However, this is still likely to be inside the 20 year marginal level for cost-effectiveness. Buildability considerations may arise, since the required density of wall ties to achieve a stable wall structure is still a matter of debate.

Increasing the roof insulation beyond 150 mm may not be cost-effective unless steps are taken to cut the cold bridges of the joists. This could be done by laying insulation in two layers, one between the joists and the other at right angles over the top.

As noted above, the Linford project showed larger floor heat losses than expected. This is an area seriously in need of research, but it does seem likely that the underfloor insulation levels specified in the Danish BR77 regulations would be a good idea in the U.K.

The Pennyland houses are ideal for the addition of conservatories on the south side; indeed two households have already done so (see figure 7.9). This will reduce the space heating demand further. The cost of the conservatory, though, must predominantly be set against the extra space that it provides rather than the extra energy saving.

Finally, although this project has concentrated on saving gas heating energy, it should be noted that the annual electricity bills for the Pennyland Area 2 (and Linford) houses now exceed their gas bills. On-peak electricity costs four times as much per kWhr. as useful gas heating energy and there are several ways in which electricity costs could be cut as well.

One way is by the use of small scale combined heat and power generation, using the waste heat of electricity production, which is only 30% efficient, to heat the houses. This would have to be done on an estate-wide basis, but could produce further large savings of possibly £100/yr with a payback time of about five years (ref.7.2).

Another way is to improve the efficiency of domestic appliances, such as refrigerators, lights, etc. This could produce savings of up to 50% of current usage (ref. 7.3).



Figure 7.9 A Pennyland single aspect house with retrofit conservatory

References

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- 7.2 D.C.Andrews and R.J.Lowe, A D.C.F. Analysis of a Totem based District Heating Scheme, ERG 036, August 1981, O.U.E.R.G.
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- 7.4 T.Kusuda and B.L.Collins, Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies, NBS Building Science Series 109, U.S. Dept. of Commerce, 1978.

CHAPTER 8

RECOMMENDATIONS AND CONCLUSIONS

- 8.1 Policy Conclusions
- 8.2 Designer's Notes
- 8.3 Future Possibilities
- 8.4 Research Methods

This chapter brings together the conclusions from the various previous chapters. It gives recommendations on how this experiment should influence future house design and future housing projects.

8. RECOMMENDATIONS AND CONCLUSIONS

8.1 Policy Conclusions

There is clear evidence in support of better insulation standards for U.K. housing. Better insulated houses can be built, they do save significant amounts of energy, people like living in them and the savings are very cost-effective. Indeed, by the time of production of this report, the energy saving measures will already have paid for themselves. The actual extra costs are very small and are unlikely to be noticed in practice since they amount to less than £450/house. This is only 2.5% of the house construction cost. There is a very strong economic case for incorporating the Pennyland Area 2 level of insulation into the U.K. Building Regulations.

Insulation costs, especially at the higher levels, appear to have been dramatically reduced since the initiation of the project. This, in part, is likely to be due to an increased use of the techniques. The use of a 100 mm filled cavity wall, for example, has been demonstrated to be as simple as a conventional 50 mm cavity, and has a very low marginal extra cost.

The Sashless windows have demonstrated that double glazing need not cost a fortune and it is recommended that further research be carried out in the development of low cost double glazing for large scale manufacture.

These low marginal insulation costs have contributed enormously to the low overall payback times of the project.

The direct gain passive solar design used at Pennyland seems to have been highly popular with the residents, but unlikely to lead to any large energy savings, mainly due to the high level of window obstruction (net curtains, etc.). The need for the direct gain design to allow sunshine unimpeded access to the interior of the house seems to be in conflict with the need of the occupants for privacy. Further research on estate layout could solve this dilemma.

It would seem desirable that the section of the Building Regulations restricting the total window area for a house is rephrased in a way that is less punitive on south-facing windows and more so on north-facing ones.

There is still plenty of scope for research in other facets of passive solar design, such as the use of conservatories and the development of selective surfaces in multiply glazed windows.

The most significant savings were achieved as a result of specifying a better boiler in the Pennyland houses. This suggests that it might be better for Building Regulations to specify an overall heating cost (under standard conditions) rather than simply standards of fabric insulation.

There are large uncertainties about ventilation rates in all the houses. It has been a piece of conventional wisdom that in better insulated houses ventilation heat losses become progressively more important. In the Pennyland houses this does not seem to have happened. Ventilation appears to have been reduced as strongly as fabric loss in these houses as compared to the Neath Hill group. This has been achieved by a combination of wall construction, window detailing, draught lobbies and the use of balanced flue boilers. The air change rates at Pennyland are perhaps a little low from a health viewpoint, though the occupants may well take the low infiltration rates into account in their window opening.

Since the Pennyland houses do seem to be very well sealed, there should be further research into the actual air change rates and the requirements for ventilation in houses, with a view to setting standards at some time in the future.

Although cost-effectiveness is a laudable criterion it should not be overstressed since there are enormous uncertainties in the real extra costs associated with individual items. From a construction point of view it probably matters more that the measures do not impede the building process. From a Local Authority estate management point of view, high occupant satisfaction and a low maintenance cost are important considerations.

8.2 Designer's Notes

Loft Insulation

Increasing loft insulation from 50 mm up to 150 mm has been very cost-effective. Increasing it further beyond 150 mm seems only marginally cost-effective unless the opportunity is taken to cut down the cold bridges of the joists. This could be done by laying the insulation in two separate layers, one between the joists and one at right angles across the top.

At high levels of insulation it is important to design in adequate ventilation in the loft space to keep roof timbers dry. The lowering of the roof line to cut solar overshadowing created a difficult insulation detail at the roof eaves and is not recommended.

Double glazing

The cheap Sashless double glazing has proved extremely cost-effective. As a double glazing system it has performed well and proved to be well sealed against air infiltration. However, there has been a certain amount of user dissatisfaction, caused mainly by the detailed design of the opening and sliding mechanism. There were also problems of condensation between the panes. These problems could be alleviated by slightly modifying the design.

Wall insulation

The Neath Hill insulated houses were given 50 mm foam urea formaldehyde insulation in the cavity. Fuel bills and a thermographic survey have indicated that it is performing properly, though measurements have not been accurate enough to fully quantify the energy savings.

Fibreglass batt insulation has been satisfactorily incorporated into the structure of the Pennyland houses at both 50 mm and 100 mm thicknesses. The energy savings at both levels have been very cost-effective with payback times in the region of 5-7 years. The 100 mm thickness is recommended for future construction and it is possible that a 150 mm thickness would be cost-effective.

The proper installation of fibreglass batts does require a small amount of extra supervision and training on site, especially in regard of proper corner detailing and the avoidance of mortar bridging.

Milton Keynes is not in a serious driving rain area and water penetration of the cavity has not been a problem. It does seem likely, though, that future U.K. construction will have to take account of these problems and may possibly require a wider cavity to retain the air gap.

Floor insulation

The thermographic survey has indicated the presence of significant floor edge heat losses both in Area 1 (no floor insulation) and Area 2 (25 mm thickness floor edge insulation). Measurements in the Linford test house showed floor heat losses considerably higher than expected. This is a subject in serious need of further research, but it seems that full underfloor insulation would be desirable for future low energy houses.

Window Shutters

Insulating window shutters of two types, a folding concertina variety and a sliding blade type, were fitted to some of the Pennyland Area 2 houses. Although the thermographic survey has shown that they do cut window heat loss, it seems unlikely that they have been used enough to justify their high cost.

Heating System

The wet radiator system used in the Pennyland houses appears to have performed very well, maintaining comfort temperatures even in some of the worst weather this century (Dec. 81). It has proved very popular with the residents. There was slight dissatisfaction with the lack of provision of upstairs heating in Area 1, but it is unlikely that it is necessary at the Area 2 insulation level.

The savings in construction cost due to a reduced heating system size in a low energy house have offset about 10% of the insulation costs.

The warm-air system installed in some of the larger Pennyland houses has not proved to be so popular and cannot really be recommended.

The use of a low thermal capacity boiler with the resulting improvement in heating efficiency has been highly cost-effective, giving a third of the project energy savings for no extra cost. However, it is likely that further large energy savings could be made by using the new range of condensing gas boilers with electronic ignition, now becoming available in this country.

Heating Controls

Measurements in the companion Linford project have shown that at high levels of insulation, the heating system must be very responsive to free heat gains from cooking as well as solar gains. The positioning of the main heating thermostat in a south-facing room will make best use of the solar gains.

Most of the Pennyland residents appear to have mastered the complexities of the timeclock and heating system programmer. Its prominent position in the kitchen is probably instrumental to this. It is recommended that clear instructions are issued, if necessary with demonstrations, especially to the elderly.

Air Infiltration

Infiltration in the Pennyland houses was much lower than expected. A primary reason for this is likely to be the use of a poured concrete construction, though many other features such as draught lobbies, window and door seals, the balanced flue boiler and the cavity insulation are likely to contribute. The resulting energy savings have been very cost-effective and do not seem to have caused serious condensation problems. It would not be wise, though, to attempt to reduce the infiltration below this level in future projects without the use of some kind of forced mechanical ventilation.

Passive Solar Design

The Pennyland project has shown that an estate can be laid out to maximise direct passive solar gains without problems, and indeed it has resulted in a well-regarded scheme, both by the occupants and by the architectural profession, winning an R.I.B.A. award.

It should not be thought, though, that the ruthless pursuit of energy cost-effectiveness in both estate and house design will automatically result in good housing. The Pennyland estate is neither the cheapest possible layout to build or to heat. It is, though, very habitable and the occupants were initially attracted there by what developers call 'kerb appeal', the external aesthetic appearance.

House layout and design is primarily an aesthetic matter and each house is someone's home. Facing houses south and avoiding overshadowing should be regarded as good practice, but the energy savings will be small compared to those from proper insulation and good heating system efficiency.

The project has not produced clear answers as to whether or not single aspect houses are more expensive to heat than dual aspect ones. In terraces, single aspect houses are certainly more expensive to build. Their justification comes in creating a mix of house designs, giving each house more individuality and marketability.

Window Area

Windows are considerably more expensive per square metre than wall. Therefore, unless their thermal performance can be dramatically improved, there is no energy cost-effectiveness reason for larger windows than necessary. The choice is again largely one of aesthetics.

Once the level of glazing has been chosen it seems desirable to concentrate the glazing on the south side of the house, though not to a level that will create gloomy rooms on the north side of the house or overheating on the south. There seems little reason to increase the south-facing glazing area beyond 40% of the south-facing wall area.

To make best use of solar gains, it is essential that windows are not obstructed by net curtains, half-drawn blinds, etc. This may be a problem of the perceived privacy of the site.

Thermal Mass

If the south-facing window area is kept to the levels used in this project, then normal medium weight construction should be sufficient to prevent summer overheating. The provision of dense concrete blockwork can add significantly to the cost of a house. It should not be used in the inner leaf of an external wall, especially at poor insulation levels, since it worsens the U-value and adds to the house heat loss. Measurements at the Linford test house suggest that the concrete floor slab, once carpeted, does not add significantly to the thermal mass of a house.

8.3 Future Possibilities

As a result of the Pennyland and Linford experiments several further areas for cost-effective improvements have become apparent.

Boiler Efficiency

Although the performance of the Pennyland and Linford gas boilers has been good, the new range of condensing gas boilers, which extract the latent heat of vapourisation of the water vapour in the flue gas, is likely to be even better. When electronic ignition is also added, there are significant extra savings to be had. These could amount to an extra £20/year per house for potentially little extra cost.

Extra Heating System Insulation

Several projects have identified high heat losses from the domestic hot water cylinder. These could be halved, saving about £3/yr for an extra expenditure of about £10 on extra tank and pipe lagging.

Extra Fabric Insulation

In the light of the Linford results, full underfloor insulation would seem to be potentially cost-effective for future lose energy houses. The lack of practical measurements for floor heat losses does make it difficult to produce a hard estimate of a payback time, but it is likely to be under ten years.

Increasing the wall insulation thickness to 150 mm from 100 mm is likely to have a payback time of about 15 years.

Cutting Electricity Costs

The electricity fuel costs of the Pennyland Area 2 houses are larger than that for gas space and water heating. This suggests that future energy conservation research should perhaps be devoted to producing efficient electric appliances, especially such items as refrigerators.

Also, efforts could be made to use the 60% of energy wasted in the generation of electricity to supply the house heating demand. Small-scale combined heat and power generation could provide further large savings of possibly £100/yr with payback times of the order of five years.

8.4 Lessons learnt from monitoring

As with most large-scale experimental projects a great deal of learning has gone on beneath the description of the project, to do with the method used, the reliability of the equipment, and the organisational problems involved. These are summarised here for the benefit of those who would like to undertake similar experiments.

8.4.1. Method

Given the level of ignorance in house monitoring at the design stage, the choice of methods and the equipment used is not bad. The combination of a low monitoring level on a large number of houses at Pennyland and Neath Hill and a higher level of monitoring at Linford on just a few houses has worked well. The two projects have complemented each other well. The Neath Hill houses have operated as a control group both for the Pennyland houses and the Linford houses and the detailed measurements in the Linford occupied houses and the test house have filled in the fine detail of the Pennyland project. The NBSLD design model has acted as a kind of go-between allowing the results to be transferred from one project to the other and giving a common synthesis of results.

Generally the simple monitoring used in the Pennyland estate has proved adequate to determine the insulation, boiler efficiency and air infiltration energy savings. It has not really been adequate to determine the solar gains and the more detailed Linford monitoring has largely filled the gap with the aid of the computer model.

Anyone wishing to carry out similar work would be well advised to follow this pattern, though with perhaps a little less emphasis on the detailed monitoring, which is very expensive. A possible scheme might be:-

- Low level monitoring - Groups of 20 houses of each type (as identical as possible). Instrumentation as for level 3 of this project - installed identically in each house.
- High level monitoring - Two or three occupied houses, possibly one of each type. The monitoring should be at the Linford level (temperature sensors in every room, etc., heat flux sensors in critical areas, such as the floor, and enough heat metering to calculate the boiler efficiencies accurately).
- Test House, intensive monitoring - This is where detailed analysis of the components of the house can be carried out. The rapid thermal calibration process developed during the Linford project suggests that the basic properties of a house, total fabric heat loss, solar aperture and much of the air infiltration response to ΔT and wind speed can be determined with only three weeks measurements. In practice, there are likely to be many questions to be answered and a whole heating season is likely to be needed.

- Pressure Tests - These have been very useful and provided a lot of information for very few hours of testing. They should be used on a sample (say 3) of each different house type.
- Thermographic Survey - This has also provided much information for just a few hours work. An external contractor who was well trained in the operation of the infra-red camera was brought in for the Linford and Pennyland houses. This has been far more fruitful than attempts by various researchers to operate two inferior cameras bought by the University.
- Weather station - This can be part of the test house system, as at Linford. The aim is to provide weather data for the whole project and the computer model.
- Computer model - Some detailed model is required to extrapolate results from one house to another and provide the 'final answers'. It helps if it can be run on the same weather data as that actually measured, allowing close comparisons with measurements.
- Social Survey This has given very valuable information on the residents' level of satisfaction and any problems. The true value of the survey is only realised when the results are analysed together with other measurements, such as the relation of condensation and mould growth complaints to measured air change rates.

Detailed comparisons of the possible results of the different monitoring levels will be found in the companion Rapid Thermal Calibration report.

8.4.2 Organisation

Hofstadter's Law - 'It always takes longer than you think, even taking into account Hofstadter's Law'.

D.F.Hofstadter - Godel, Escher & Bach.

It is a sad fact of life that field trials take on average three times longer than originally estimated. Time and again researchers set forth to do monitoring with the idea that if only they can get their monitoring equipment to read in some temperatures then all will be well and the project answers will fall out by magic (and the final project report will be written in the next week!).

Things are in practice much more complicated. This report is not the place to launch into a description of all the possible monitoring methods. Much of this area is exhaustively covered in the S.E.R.C. Field Trial Monitoring Notebook (ref. 8.1).

The most important advice that can be given to those undertaking similar projects is:-

Building schedules for large numbers of houses are inflexible. Make sure that monitoring contracts are signed and researchers hired well before work on site needs to start. Preferably, a monitoring contract should be given at least a year before building starts.

Make sure that there is adequate cash available to purchase all the equipment and pay for the installation. For a large project this really needs someone who understands accounts. A computer accounting system is probably a good idea.

Test equipment before it is installed, otherwise it will create enormous problems later.

Train technicians before installation of equipment.

Make sure that there is power available on site for installation work. This may require a generator.

Make sure that there is a tea room/W.C. available on site. The Linford test house was very useful on this project, but on another (Bebington) one had to be built specially.

Make sure that the installers have transport (and a travel budget).

Try to do the installation in the summer. Much of the Pennyland/Linford installation was done in bitterly cold weather (see figure 4.25).

Inspect the installation thoroughly. Check that all equipment is put in the same (and right) way round. Be prepared to have things changed even if this creates problems with the builders/plumbers/electricians. The results of the project may depend on it.

Start work on the database management system before installation. Do not underestimate the complexity of the task, especially if the monitoring is of the 'measure everything in sight' type as at Linford. Fortunately computing advances have meant that managing a Pennyland style database is not too onerous.



Figure 8.1 Researchers Alan Horton, John Butler & Jill Mabbot brave arctic weather to erect the Linford weather station.

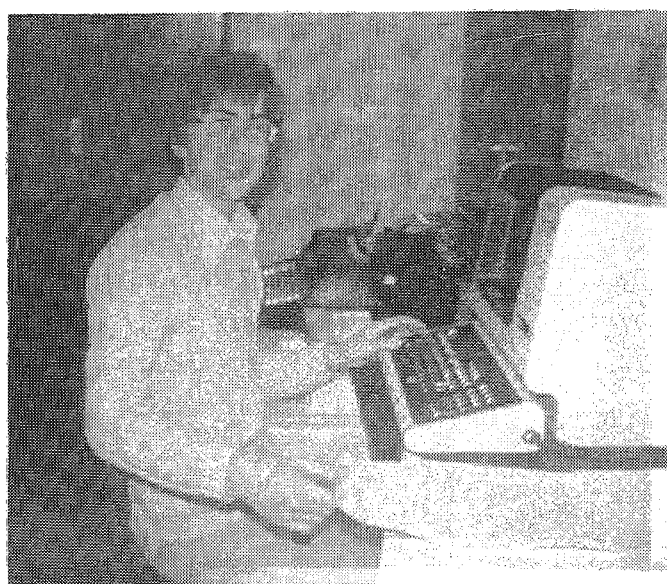


Figure 8.2 Jeremy Chatfield masterminding the computer database.

Check new data as it comes in. If you haven't checked it within a week of measuring, you shouldn't have measured it in the first place.

Do not underestimate the time and effort in teaching others to use the computer and database programs fluently and confidently.

Get a good computer graphics package to inspect the data. It works wonders in trying to understand things and weed out errors.

Do not expect to delegate tedious tasks such as data cleaning to people with limited computer knowledge. These tasks can be done by relatively experienced people as long as an experienced researcher is always on hand in the same room.

To avoid data mix-ups when meters are being read which look similar (such as two identical gas meters), make sure that they are clearly marked, and/or are likely to show vastly different numbers.

Try to arrange that if the database handling programs are not working for some reason, other data tasks such as cleaning and checking can be done. This avoids having idle hands, but tends to need a fair amount of disc space in the computer for temporary data storage.

Calibrate dubious instruments, such as heat meters and doubtful D.T.I.'s before and after the measurement period. Keep track of which instrument was in which house.

Do not underestimate the overall analysis task. Although the original concept of this project was based on 'average performance', each house has had to have individual attention and data cleaning has meant that every week's data has had to be scrutinised for consistency.

Finally, do not underestimate the task of report writing. The sponsors would like to understand the answers even if the researchers don't. It requires a lot of explanation and a lot of graph drawing. It helps if the database computer can do this easily. For every graph in this report, at least ten have been drawn on the way.

8.4.3 Further Research

Future work undertaken with a view to reducing energy consumption in the domestic sector should include:-

- a) the factors affecting the air leakage of a house
- b) the feasibility of measuring ventilation rates in occupied houses
- c) the feasibility of controlling ventilation rates by airtight construction and the use of either mechanical ventilation or controllable natural ventilation.
- d) the mechanisms of floor heat loss
- e) the development of easily understood heating controls
- f) the effect of controls on heating systems
- g) ways of reducing standing losses from heating systems (pilot lights, heat losses from hot water cylinders, etc.)
- h) way of reducing the use of electricity in lights and appliances.

Reference

8.1 Field Trial Monitoring Notebook, ed. B.Day, S.E.R.C., 1982.

APPENDIX 1

COSTS OF DUAL AND SINGLE
ASPECT HOUSES

APPENDIX 1: Detailed costs of Pennyland dual and single aspect houses

This appendix presents detailed costings for the Pennyland dual and single aspect houses.

The costing exercise was carried out by a firm of chartered quantity surveyors in a standard manner used for the design studies for other Department of Energy passive solar house designs.

Costs are for semi-detached houses in both cases. This corresponds roughly to the average level of terracing at Pennyland. The costs are for houses at the Area 2 level of insulation and are calculated as if the houses had been built in March 1984. They also assume conventional construction techniques rather than the Mowlem poured concrete construction which cannot really be costed properly for one-off house construction. Thus external walls are assumed to have lightweight blockwork inner leaves and partition walls are assumed to be of timber stud partitioning. Other features are as built.

The cost of the extra thermal mass used in the Pennyland estate is dealt with in Chapter 7.

A.1.2.

Table Al.1

ETSU PASSIVE SOLAR STUDIES: STANDARD FORM OF COST ANALYSIS - DOMESTIC BUILDINGS

ELEMENTAL COST SUMMARY: PENNYLANDS HOUSING PROJECT, MILTON KEYNES

Brief description of house type: 3 bedroom, 5 person semi-detached

SINGLE ASPECT - AREA 2 INSULATION LEVEL

Element	Element cost incl. prelims. £	Element quantity m ²	Element unit rate £/m ²
1. substructure and ground floor	2220	45	49.33
2. upper floors	1032	41	25.17
3. staircase	643		
4. roof	2353	59	39.88
5. external walls	3382	89	38.00
6. windows and external doors	1887	20	94.35
7. party walls	442	30	14.73
8. internal walls	1378	84	16.40
9. internal doors	1386		
10. mechanical services	3332		
11. electrical services	943		
12. sundry items	1500		
13. special features	500		
Total estimated cost	20998		

A.1.3.

Table A1.2

ETSU PASSIVE SOLAR COST STUDIES: STANDARD FORM OF COST ANALYSIS -
DOMESTIC BUILDINGS

ELEMENTAL COST SUMMARY: PENNYLANDS HOUSING PROJECT, MILTON KEYNES

Brief description of house type: 3 bedroom, 5 person semi-detached

DUAL ASPECT - AREA 2 INSULATION LEVEL

Element	Element cost incl. prelims. £	Element quantity m ²	Element unit rate £/m ²
1. substructure and ground floor	2214	44	50.32
2. upper floors	1059	43	24.63
3. staircases	409		
4. roof	2646	59	44.85
5. external walls	3268	86	38.00
6. windows and external doors	1502	16	93.88
7. party walls	560	38	14.73
8. internal walls	1058	69	15.33
9. internal doors	1006		
10. mechanical services	3332		
11. electrical services	943		
12. sundry items	1500		
13. special features			
Total estimated cost	19497		

Table A1.3

AREA COMPARISON: SINGLE AND DUAL ASPECT HOUSES

Function	Single aspect		Dual aspect	
	m ²	%	m ²	%
<u>Habitable areas</u>				
living room	13.4	14.9	15.5	17.4
kitchen/dining	15.6	17.3	14.9	16.7
bedroom 1	11.8	13.1	13.5	15.2
bedroom 2	7.3	8.1	13.1	14.7
bedroom 3	10.5	11.7	5.1	5.7
Total habitable	58.6	65.1	62.1	69.7
<u>Balance areas</u>				
bathroom	3.1	3.4	3.8	4.3
WC	1.3	1.4	-	-
WC/cloaks	1.4	1.6	1.4	1.6
storage	5.4	6.0	1.7	1.9
circulation	16.0	17.8	16.6	18.7
partitions	4.2	4.7	2.8	3.1
bin and meters	-	-	0.6	0.7
Total balance	31.4	34.9	26.9	30.3
Total	90.0	100.0	89.0	100.0

David, Belfield and Everest.

APPENDIX 2

THE 't' TEST FOR GROUP COMPARISONS

APPENDIX 2: The 't' test for group comparisons

Randomness Versus Sample Size

The most infuriating feature of housing research is that houses are occupied by real people with wide variations in behaviour. These wide variations produce enormous spreads of space heating demands, making it very difficult to see whether some energy saving measure is actually having any effect. Figures A2.1 - A2.3 show distributions of gas consumptions for three different sets of nominally similar houses. There are wide spreads, some of which will be due to the minor differences in house design, but most of which are due to the differences in behaviour of the occupants. In the group of 57 houses in figure A2.1, the distribution is so ragged that it is very difficult to say what is the true average of the data set of which these are a random sample. As we increase the number of houses in the sample (figures A2.2 & A2.3) the distributions become more Gaussian in shape and we have more confidence in assigning an 'average' gas consumption.

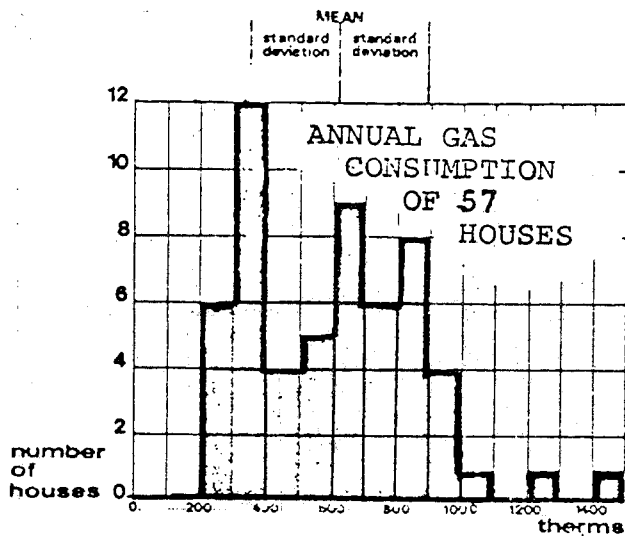


Figure A2.1 (Ref.1)

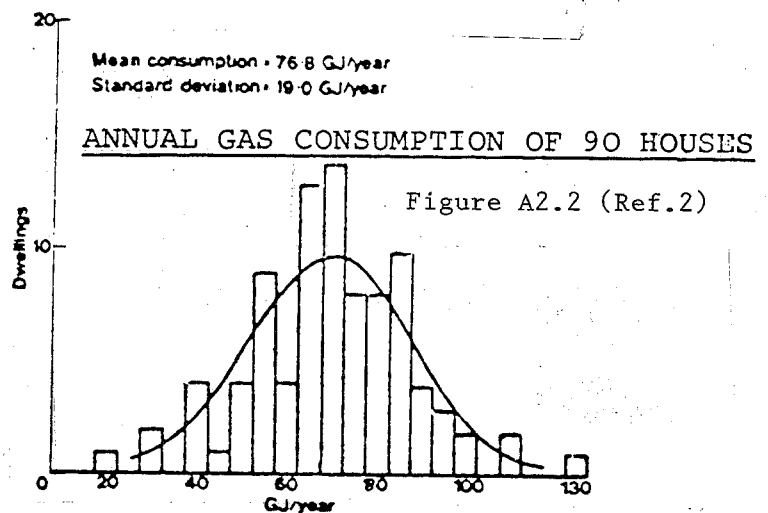


Figure A2.2 (Ref.2)

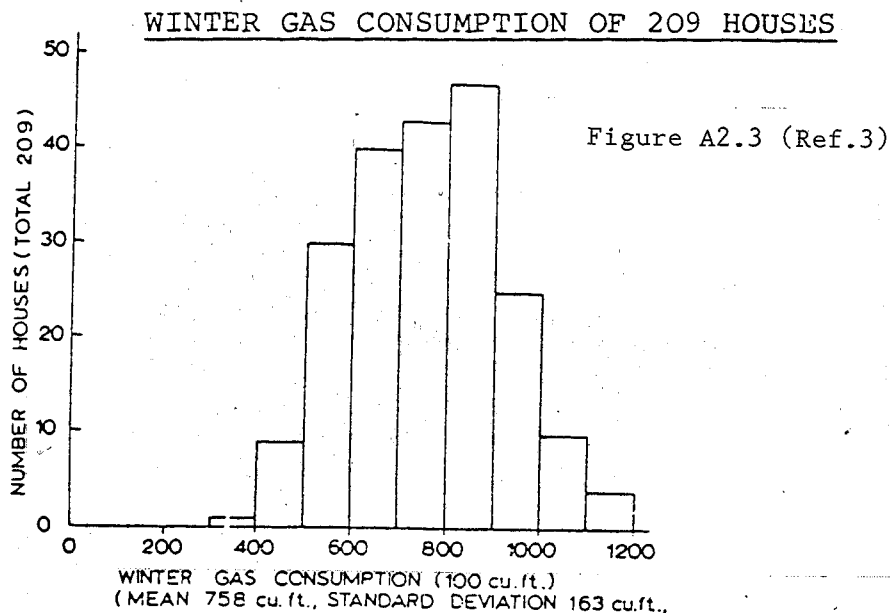


Figure A2.3 (Ref.3)

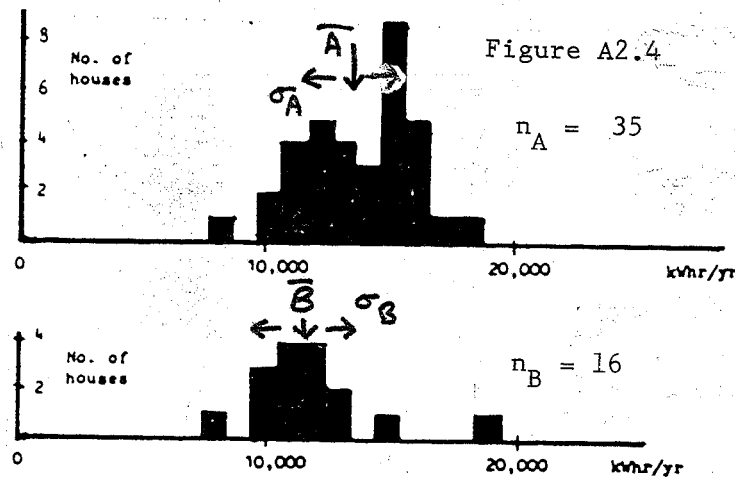
The 't' test

Let us suppose that we have two sets of houses, Pennyland Area 1 & Area 2, for example, and that we have made some modification to one set so that the annual gas consumption is reduced by 2000 kWh/yr. Having measured the actual annual gas consumptions, we end up with two ragged distributions as in figure A2.4. The change in gas consumption is small compared to the behavioural spread in consumptions.

It may be, therefore, that we have not actually saved any energy at all, but have merely chosen by chance a set of inhabitants in one set of houses who happen to use less energy than in the other set. How can we be sure that our saving is really there?

We can assess this problem using the 't' test for statistical significance. If we had a very large number of houses in each group, we would expect the two groups to exhibit smooth Gaussian distributions such as in figure A2.3 and we would be very certain that there was, in fact, a difference in energy consumption between the two house designs.

If we only have a small number of houses in each group, we will have a random selection from these smooth Gaussian distributions making up our two ragged samples:-



Let us say that the two groups have means A and B , and standard deviations σ_A and σ_B . We wish to know whether the difference between the means can reliably be attributed to some modification to the houses.

First we must calculate a pooled estimate of a standard deviation for a common data set to which both groups might belong:-

$$\sigma_{AB} = \sqrt{\frac{(n_A - 1) \sigma_A^2 + (n_B - 1) \sigma_B^2}{n_A + n_B - 2}}$$

where n_A & n_B are the number of houses in each group.

A.2.3.

From this we can then calculate a statistical significance figure 't':-

$$t = \frac{\bar{B} - \bar{A}}{\sigma_{AB} \sqrt{1/n_A + 1/n_B}}$$

We can then consult a table of values of 't' to find the probability that the difference in means is not just due to chance.

For relatively large numbers of houses (n_A and n_B greater than about 20), in order to be sure that our difference actually exists, 't' must be greater than:-

2.0 for 95% confidence (19-1 against chance)
 1.7 for 90% confidence (9-1 against chance)
 1.0 for 70% confidence (7-3 against chance)
 0.68 for 50% confidence (evens)

If we say that the two groups have the same standard deviation σ , and that they each have the same number of houses, n, then the 't' test reduces to:-

$$t = \frac{(\bar{B} - \bar{A}) \sqrt{n}}{\sqrt{2} \cdot \sigma}$$

Put another way, we can plot n, the number of houses to detect a given energy saving to a particular confidence level, against F, the energy saving as a fraction of the standard deviation:-

$$F = \frac{\text{Detected energy saving}}{\text{Standard deviation}} = \frac{\bar{B} - \bar{A}}{\sigma}$$

$$\text{Therefore the required number of houses in each group} = \frac{2 t^2}{F^2}$$

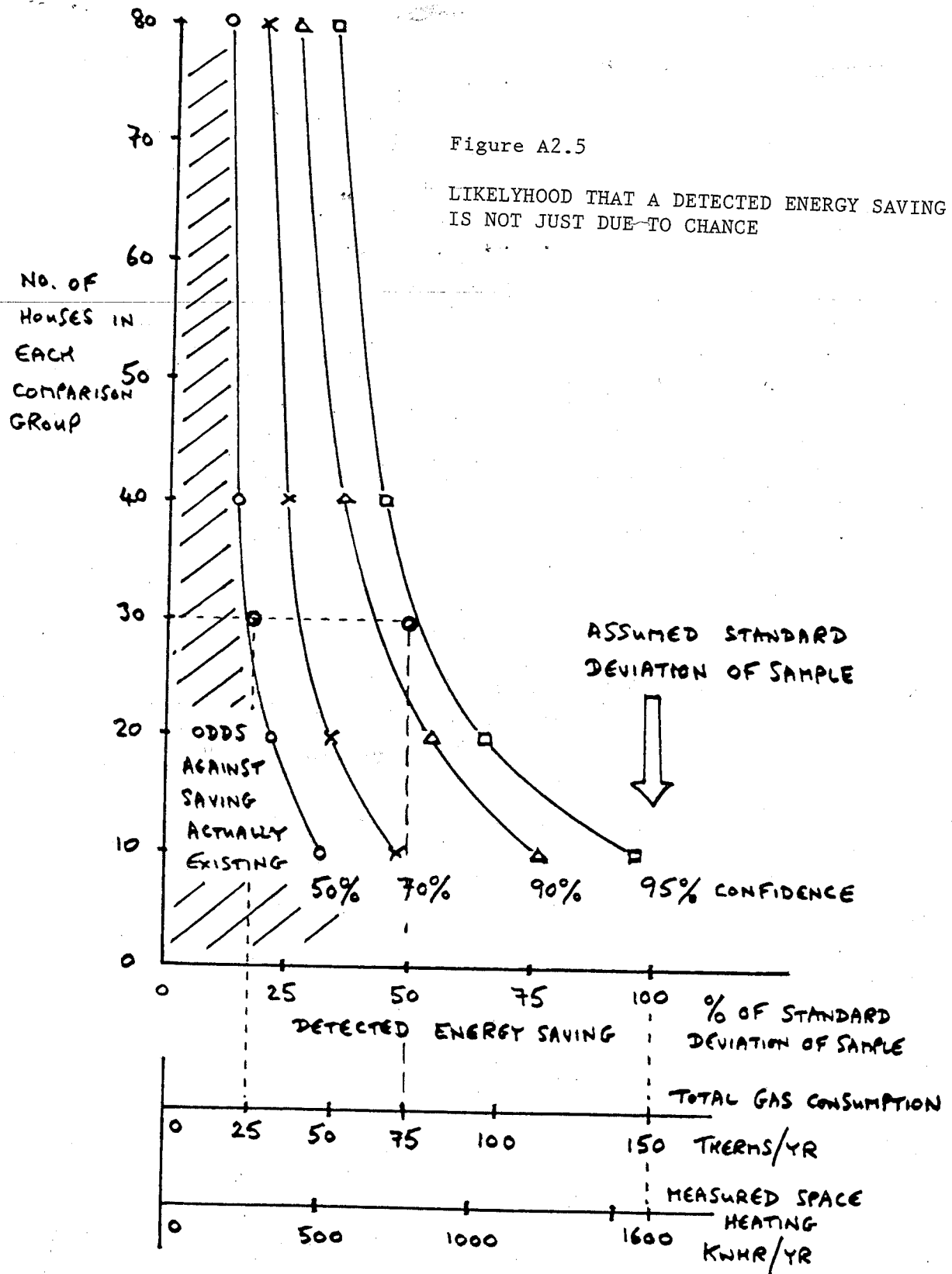
This graph is plotted out in figure A2.5.

Now, if we knew a likely figure for σ , we could make estimates of the number of houses required to detect a given energy saving between two groups.

In the distribution of figure A2.1, the standard deviation, σ , is about 150 therms/yr (approx. 4,500 kWh/yr delivered). As an example, let us suppose that we had detected a difference of 75 therms/yr between two samples of 30 houses each. Using figure A2.5 we can show that there is 95% confidence that there really is an energy saving.

We can extend the method and ask "What is the probability that our saving is greater than 50 therms/yr?". We can now look up on the graph the probability of detecting a difference of 75-50 = 25 therms/yr, and we find that we only have a 50% confidence level.

This may all sound extremely mathematically abstruse. However, the field trial from which this theory was taken (ref. 4) used such small numbers of houses and detected such small changes in energy consumption that



A.2.5.

the results included values of 't' down to 0.05, a 96% confidence that there was no difference between the samples!

The importance of this type of analysis is that it shows the need for large groups of near identical houses in each group to get hard answers. For insulation comparisons involving quite major step changes, such as those between Pennyland Area 1 and 2, groups of about 30 houses each are adequate to detect and possibly quantify the savings. Smaller energy savings such as those due to passive solar design (of the order of 500 kWh/yr) would need comparison groups of 100 or more houses each.

The basic impossibility of detecting these small energy savings by simple comparison of annual fuel bills was realised at the outset of the Pennyland project and lead to the installation of further monitoring equipment with a view to 'house characterisation', i.e. attempting to relate the weekly energy consumption of each house to temperature and solar radiation. Since very little of this kind of work had been carried out prior to 1977, it was not possible to carry out a similar exercise on the potential success of this method.

References.

- A2.1 A.Horton & S.Grove, 'Milton Keynes Solar House', Polytechnic of Central London, 1979.
- A2.2 G.A.Pickup & A.J.Miles, 'Energy Conservation - Field Studies in Domestic Heating', Inst. Gas Engineers Communication, 1086, 1978.
- A2.3 R.H.Socolow, 'The Twin Rivers Program on Energy Conservation' ERG77/19, Energy Research Group, Cambridge (Mass.), 1977.
- A2.4 Electricity Council, 'Economics of Thermal Insulation', Job No.83, 1975.

APPENDIX 3

DETAILED DRAWINGS

APPENDIX 3: Detailed drawings of Pennyland and Neath Hill houses

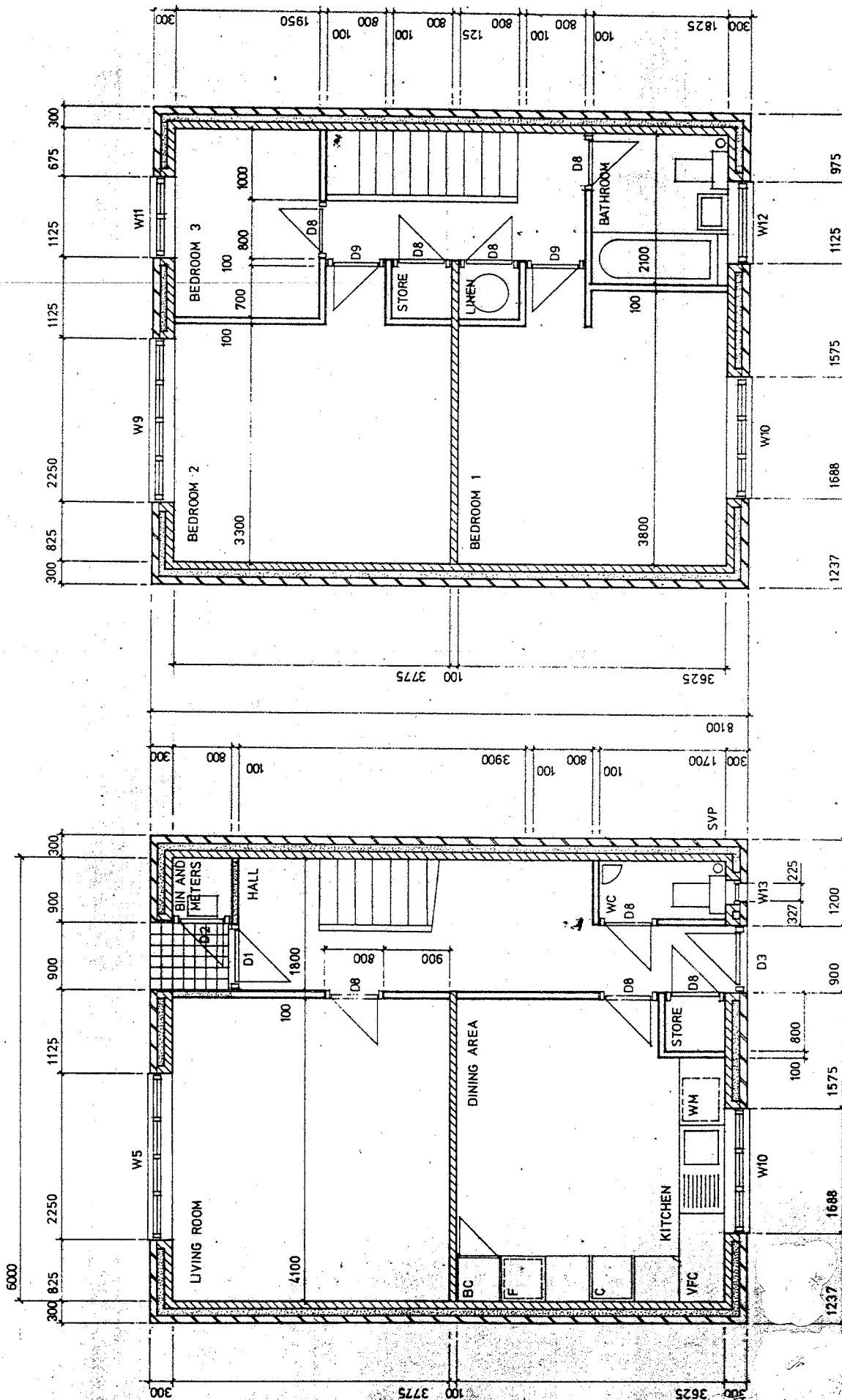
This appendix presents, with little comment, plans, elevations and heating system layouts for the Pennyland and Neath Hill three bedroom houses that have been studied in detail. Photographs and small sketch plans of the Pennyland houses will be found in the main text, but the detailed drawings are presented here for reference.

The Pennyland houses

Figures 1 to 11 show floor plans, front and rear elevations, window and door details for the Pennyland dual and single aspect houses. For completeness floor plans and elevations for both types of dual aspect house (types 5pd and 5pe) are shown.

Figure 12 shows the construction details relating to the insulation and the three different types of floor slab arrangement used according to the precise ground conditions. These affect the positioning of the floor insulation.

Figures 13 and 14 show the positioning of the radiators in the single and dual aspect houses. The distributing pipework was run through the intermediate floor.



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Project	Project no.	Checked	Drawn	Date	Scale	Revision
PENNYLANDS 1	60141		TY	MAR 78	1:50	60141/L/23
Drawing title						
SP DUAL ASPECT TYPE D						
FLOOR PLANS						

Fig 1 Pennyland dual aspect (5d) plans

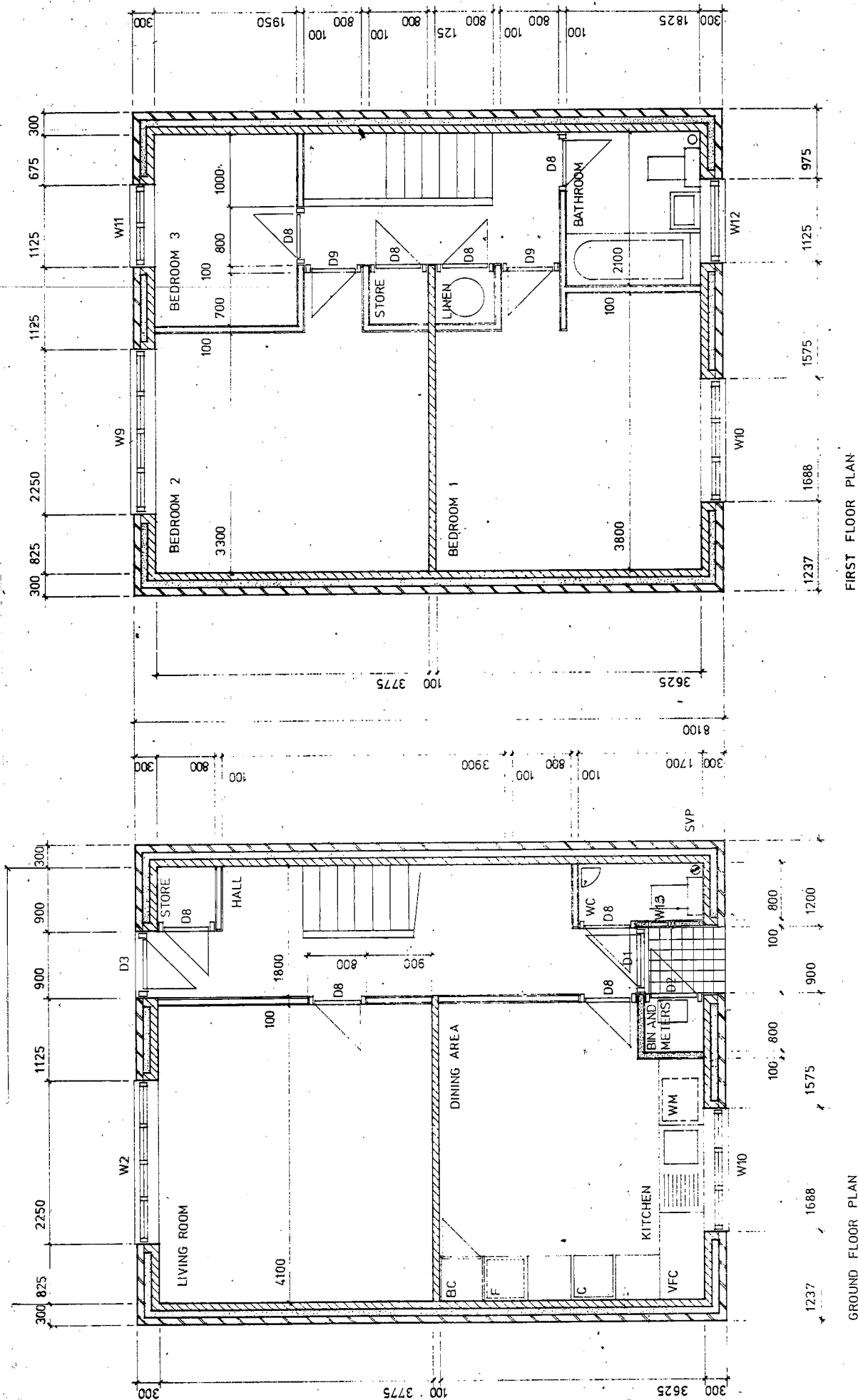
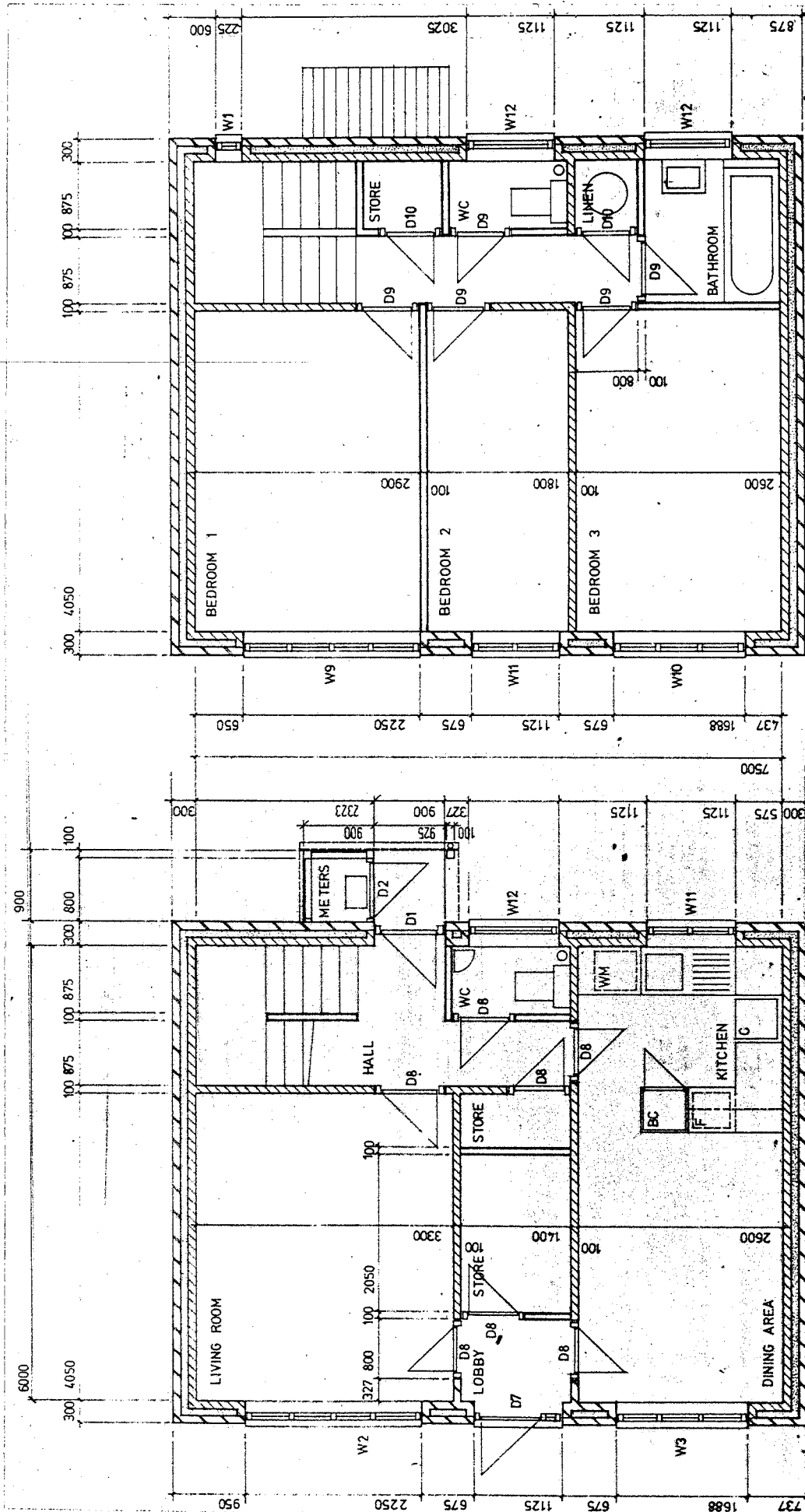


Fig 2. Pennyland dual aspect (Se) plans.

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Project	Drawn	Checked	Project no.	Source ref
PENNYLANDS 1	TY		60141	
Drawing title	Date	Scale	Drawing on	Revision
5P DUAL ASPECT FLOOR PLANS	MAR 78	1:50	60141/L/24	

010311



FIRST FLOOR PLAN

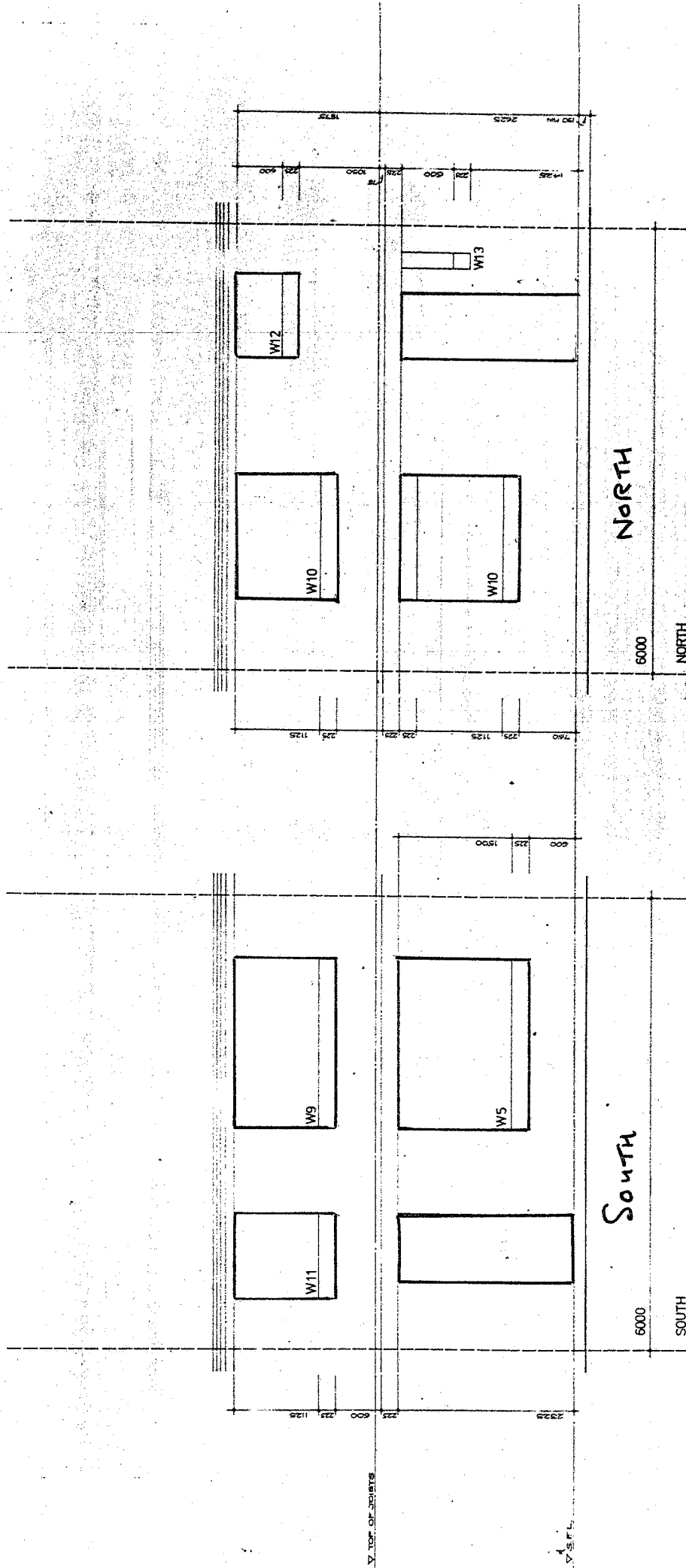
GROUND FLOOR PLAN

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 Watlington Estate, Watlington, Milton Keynes, MK17 8LJ
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Drawn	TY	Date	APR 78
Scale	1:50	Project no.	60141/L/25 A
Project	PENNYLANDS 1	Drawn by	TY
Project	5P SINGLE ASPECT	Project no.	60141/L/25 A
Project	FLOOR PLANS	Project no.	60141/L/25 A

Fig3 Pennyland single aspect (5f) plans



TYPE D DUAL ASPECT FACADES

No Date Revision

Figure 4.

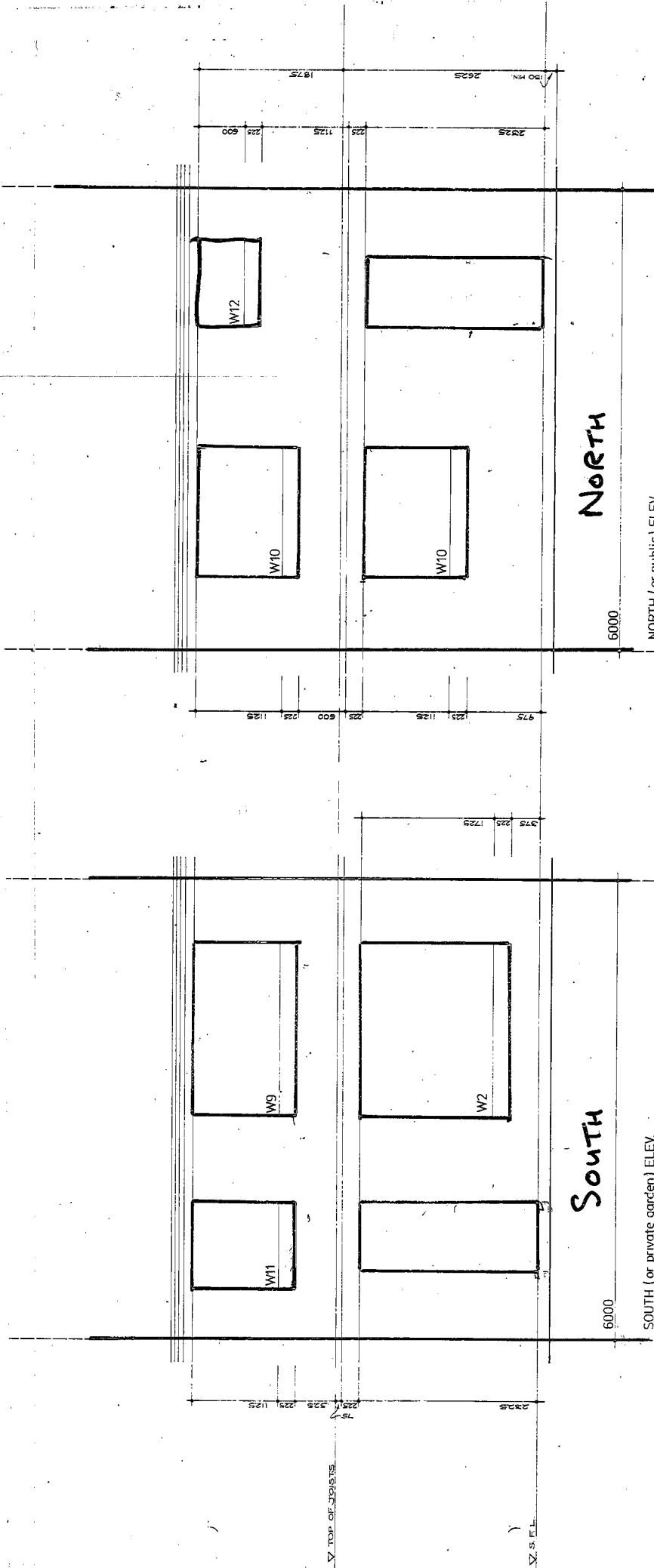
Milton Keynes Development Corporation
Wendon Tower, Wendon, Milton Keynes MK17 8LX
Telephone: Milton Keynes 74000



Project: PENNYLAND 1
Drawing title: ELEVATIONS HOUSE TYPE D
SP DUAL ASPECT
Drawing no: 6014/L/38
Scale: 1/50
Date: 6014/L/38
Revision: 6014/L/38
Drawing no: 6014/L/38
Scale: 1/50
Date: 6014/L/38
Revision: 6014/L/38

NY 77307 D

A.3.6.



TYPE E DUAL ASPECT FACADES

No. Date Revision

Face S

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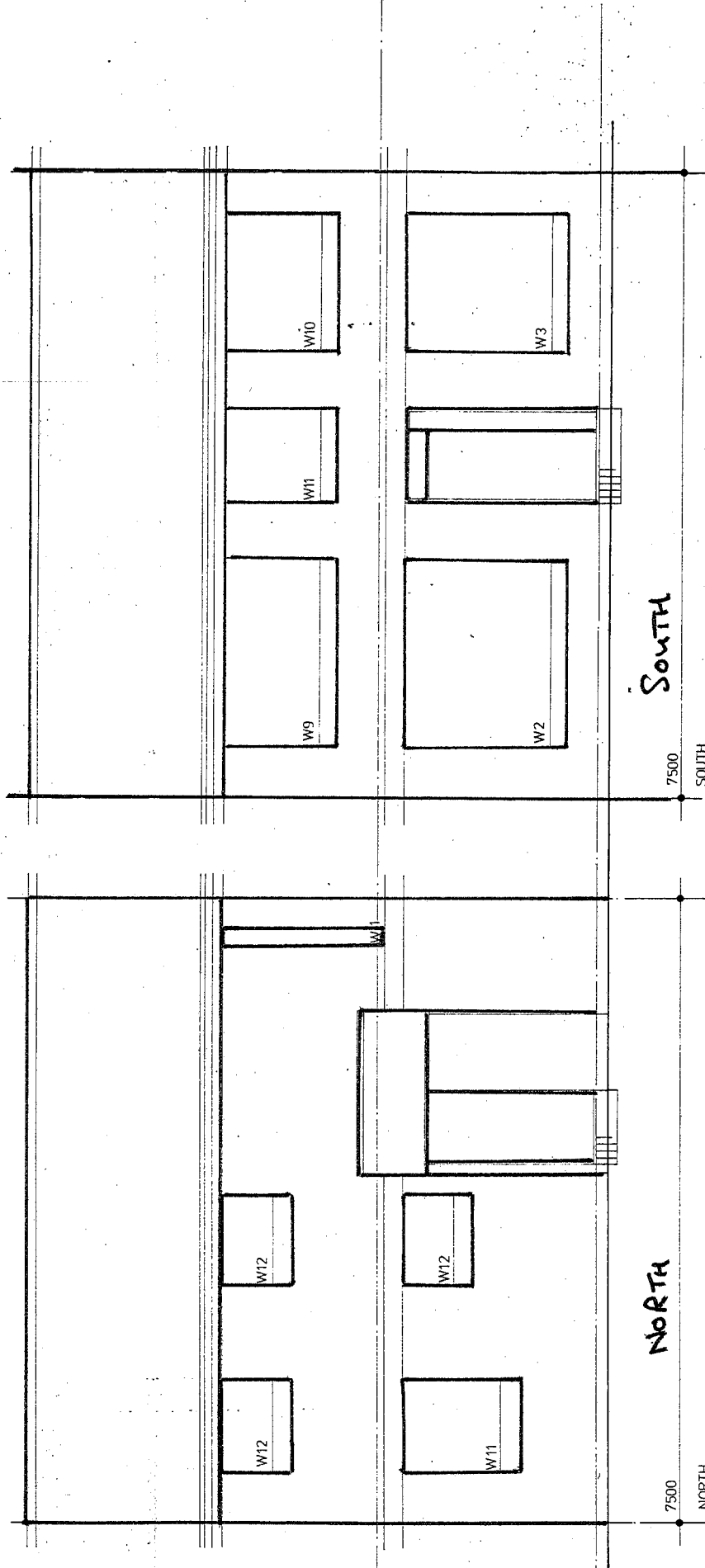


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Drawing no. 60141
Checked
Drawn
Source ref. 60141

Revision
Drawing no. 60141/L/39
Scale 1:50
Date

ELEVATIONS HOUSE TYPE E
5P DUAL ASPECT

MY 77307



TYPE F SINGLE ASPECT FACADES

Figure 6.

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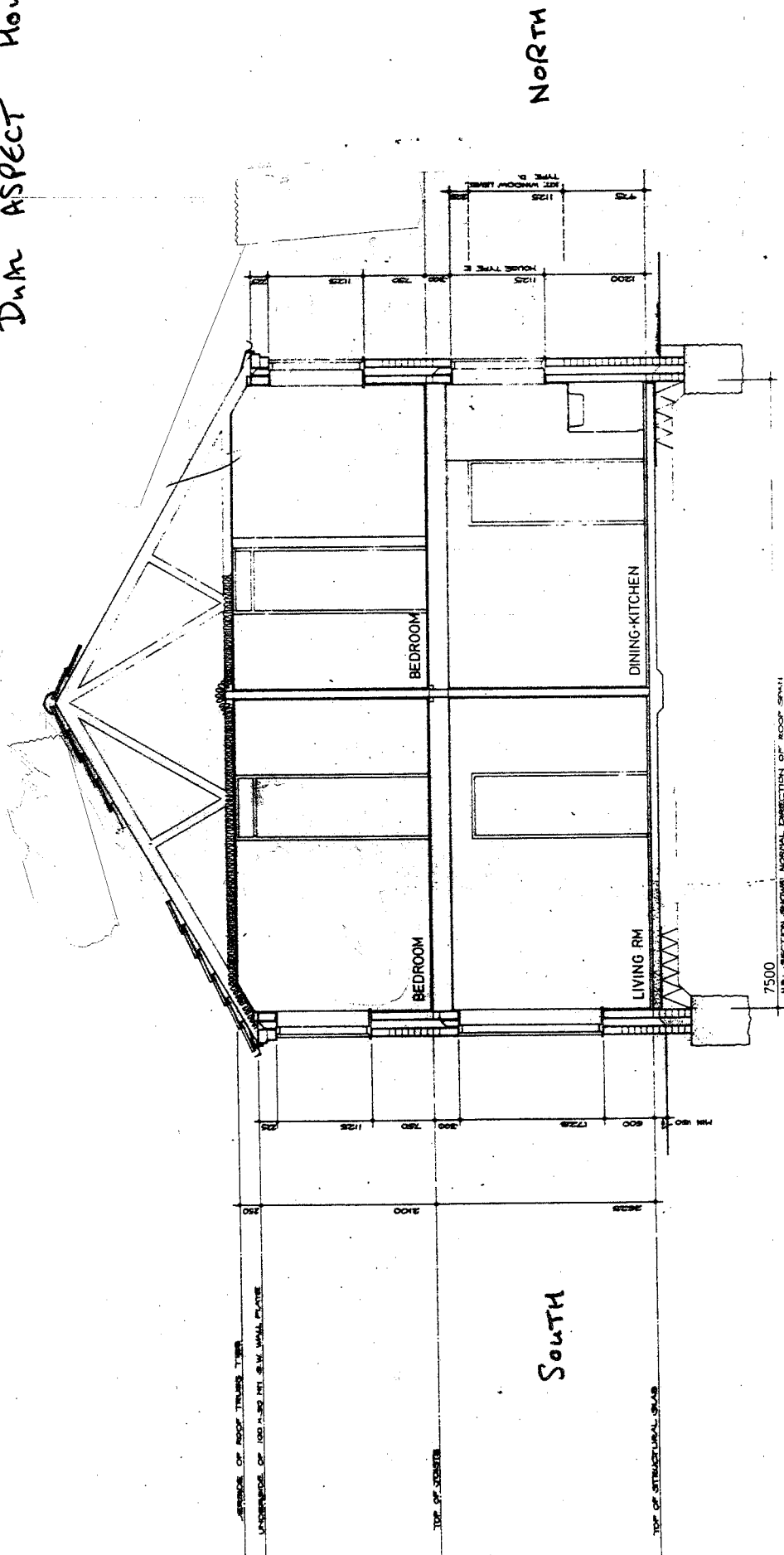
No.	Date	Revision

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Drawing title	Date	Scale	Drawing no.	Revision
ELEVATIONS HOUSE TYPE F 5P SINGLE ASPECT		1:50	60141/L/40	

CROSS - SECTION

DATA ASPECT HOUSES



OUTLINE SPECIFICATION NOTES AS DRAWING NO 604H/L/32.

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Project	Drawn	Checked	Project no.	Source ref.
	11.0		604/4	

Drawing title	Date	Scale	Drawing no	Revision
PENNYLAND 1	JLS		00141	

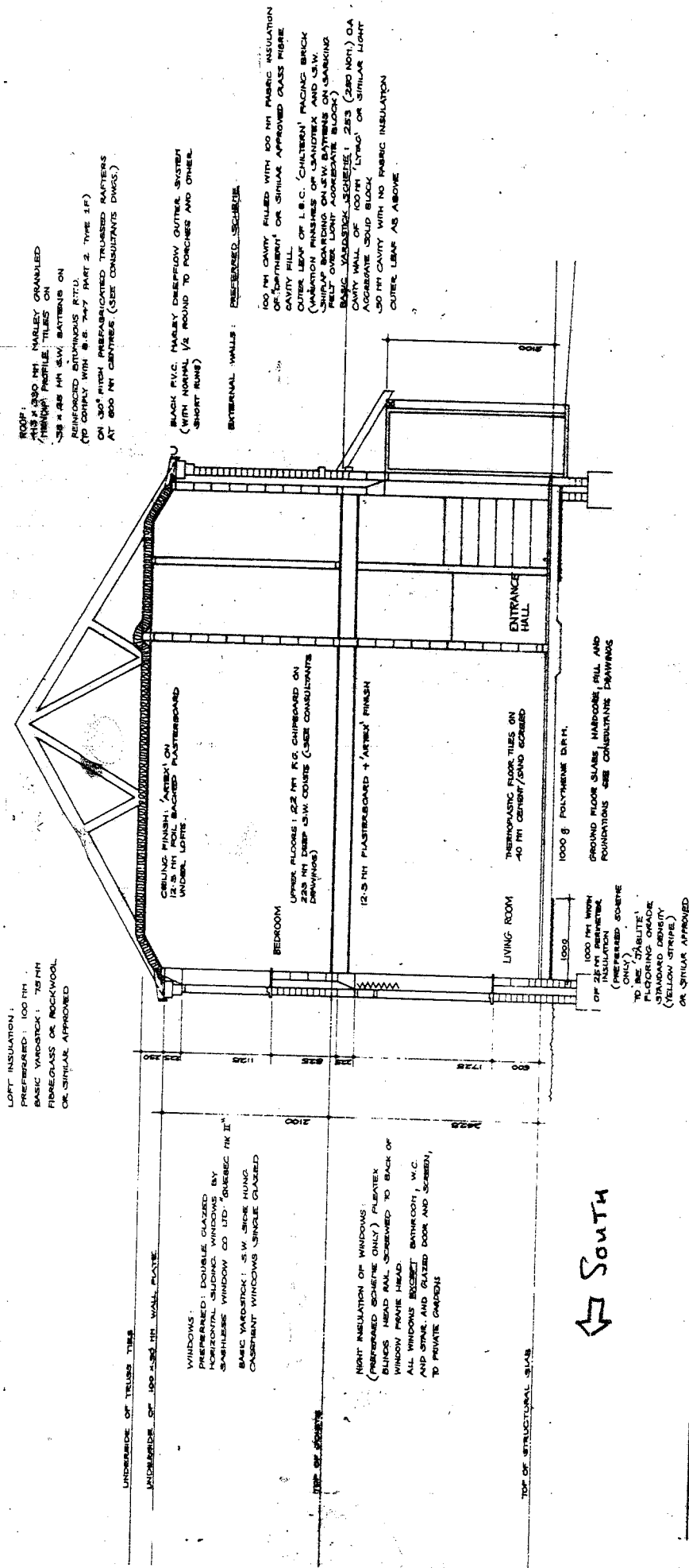
TYPICAL SECTION

SP DUAL ASPECT TYPES D & E 1:50 60/14/15/31

773071

CROSS - SECTION SINGLE ASPECT Houses

Figure 8



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Waverdon Tower, Waverdon, Milton Keynes MK17 8LX
Telephone Milton Keynes 74000



Project
Drawing title

PREPARED

Drawn

Checked

Scale

Typical section
Single aspect houses

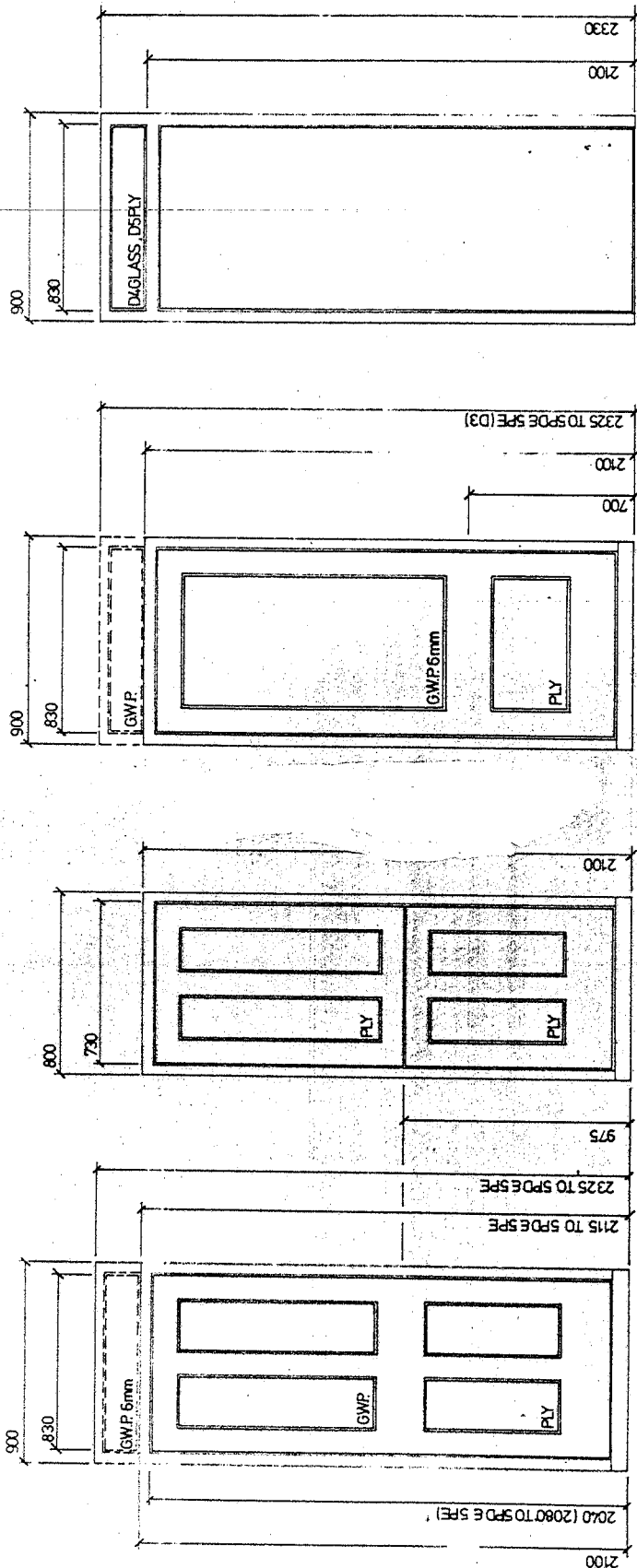
Date

Project no.

Scale

1:50 80/11/82

A.3.10.



826 x 2040 x 10mm PRE-FINISH
 LIPED INSULATED STOREY-HEIGHT
 DOORSET

826 x 1981 x 10mm REAR DOOR
 BASED UPON EXG WITH
 NON-STANDARD MIDDLE RAIL
 800mm. DOOR COMPLETE WITH
 FACE FIXED WEATHER MOUNTING

726 x 1060 x 10mm METAL
 CUPD DOOR WITH 100mm
 MOUNTIN.
 726 x 815 x 10mm RAIL
 STORE DOOR WITH 100mm
 MOUNTIN AND FACE FIXED
 WEATHER MOUNTING

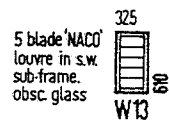
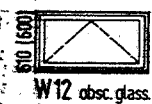
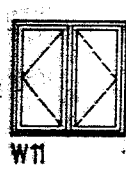
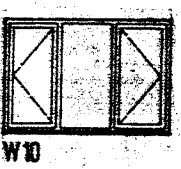
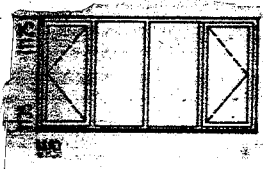
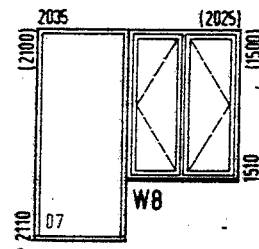
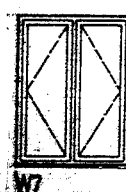
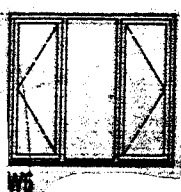
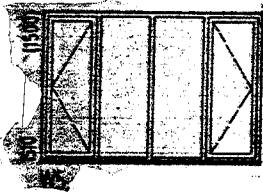
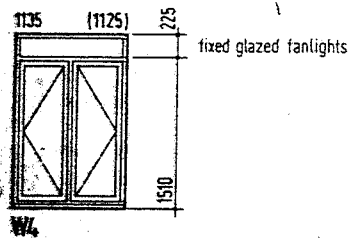
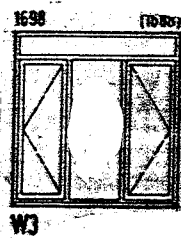
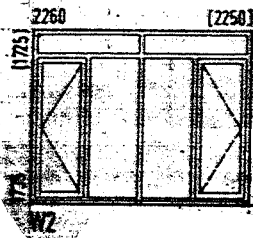
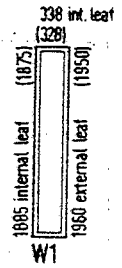
826 x 1981 x 10mm EXTERNAL
 DOOR BASED UPON EXG WITH
 NON-STANDARD MIDDLE RAIL
 800mm AND MOUNTIN 100mm.
 DOOR COMPLETE WITH FACE
 FIXED WEATHER MOUNTING

FIGURE 9.
 PENNYLAND
 DOOR TYPES



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Project	Drawn	Checked	Project no	Source ref
PENNYLAND 1	MT		6041	
Drawing title	Date	Scale	Drawing no	Revision
A.3.10. A.3.10.10.1	7/93	1:20	6041/1/34	



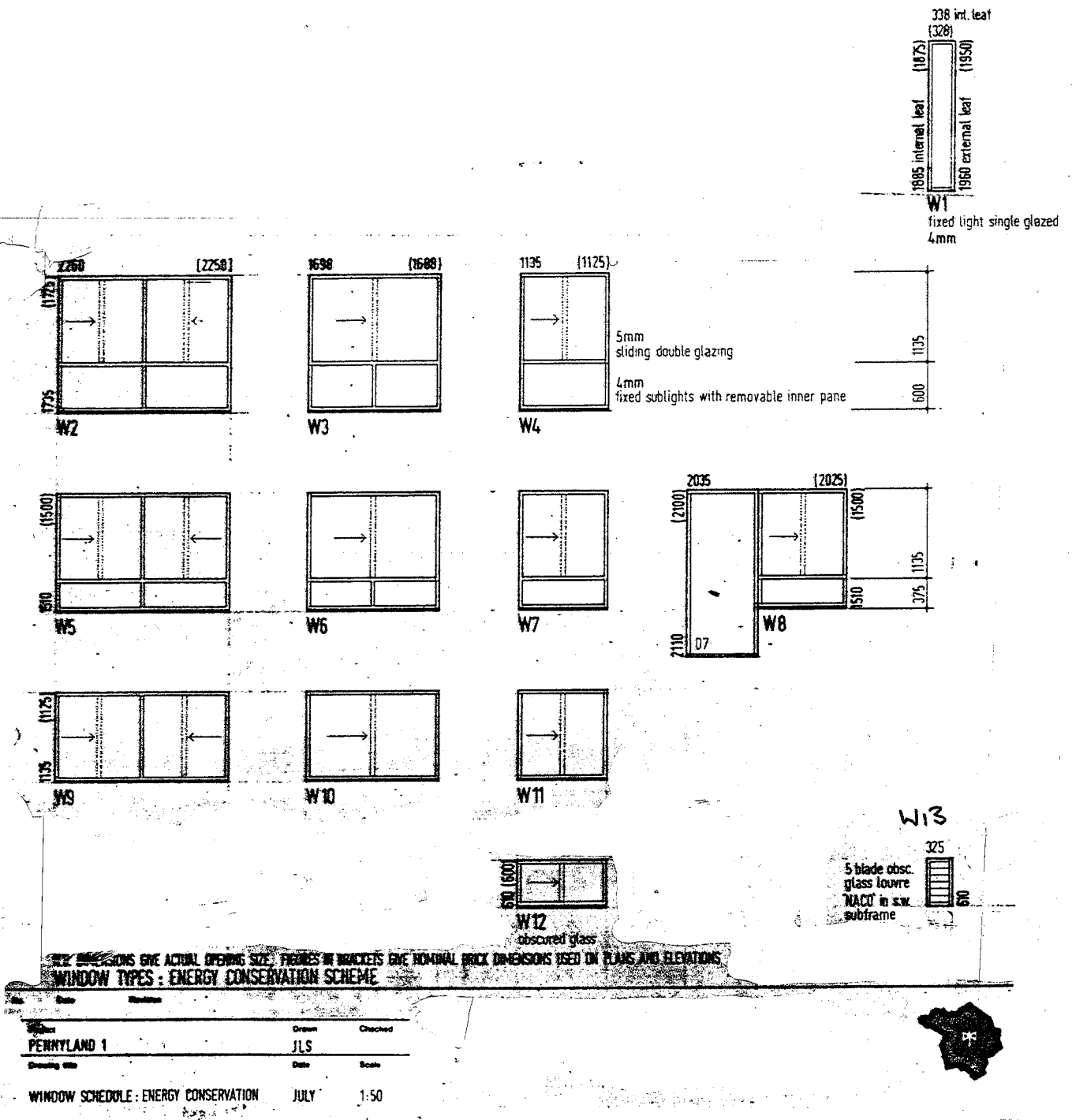
N.B. DIMENSIONS GIVE ACTUAL OPENING SIZE, FIGURES IN BRACKETS GIVE NOMINAL BRICK DIMENSIONS USED ON PLANS AND ELEVATIONS
WINDOW TYPES - BASIC YARDSTICK SCHEME

No.	Date	Revision	Drawn	Checked	Project no.	Source ref.
1			JLS		60141	
			Date	Scale	Drawn by	Revision
WINDOW SCHEDULE: BASIC YARDSTICK						



PENNYLAND AREA 1 WINDOW TYPES (SINGLE GLAZED)

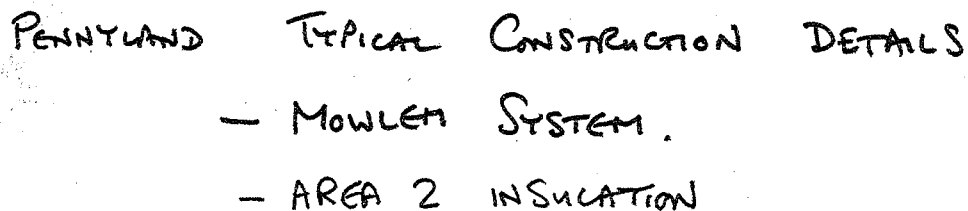
FIGURE 10.



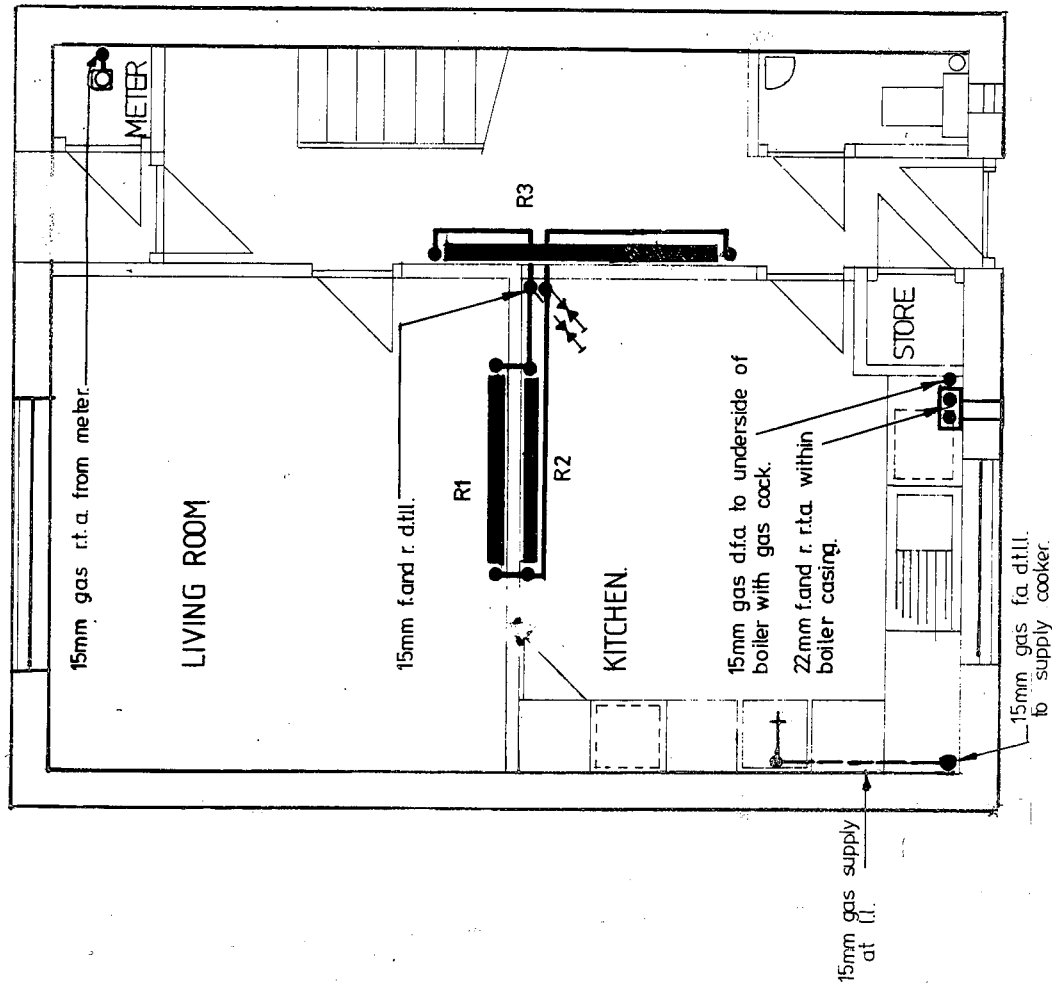
PENNYLAND AREA 2 WINDOW TYPES

FIGURE 11.

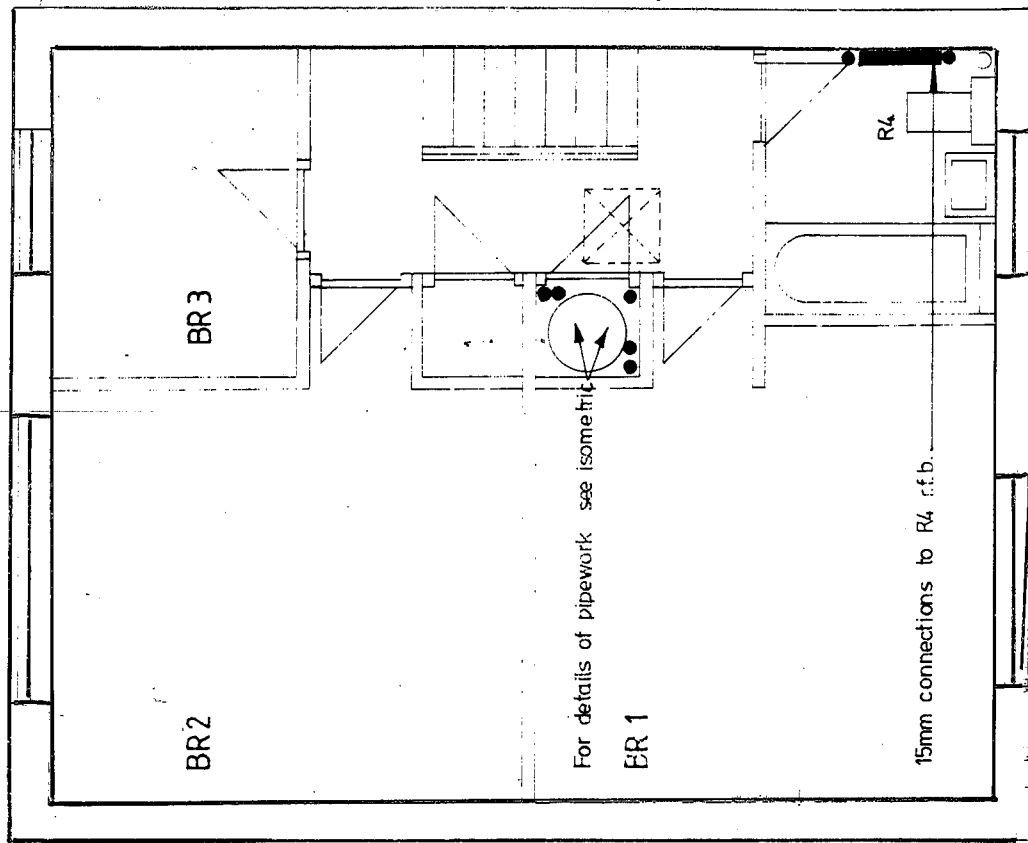
SASHLESS DOUBLE GLAZING
EXCEPT W1 & 13 SINGLE GLAZING



Ground floor

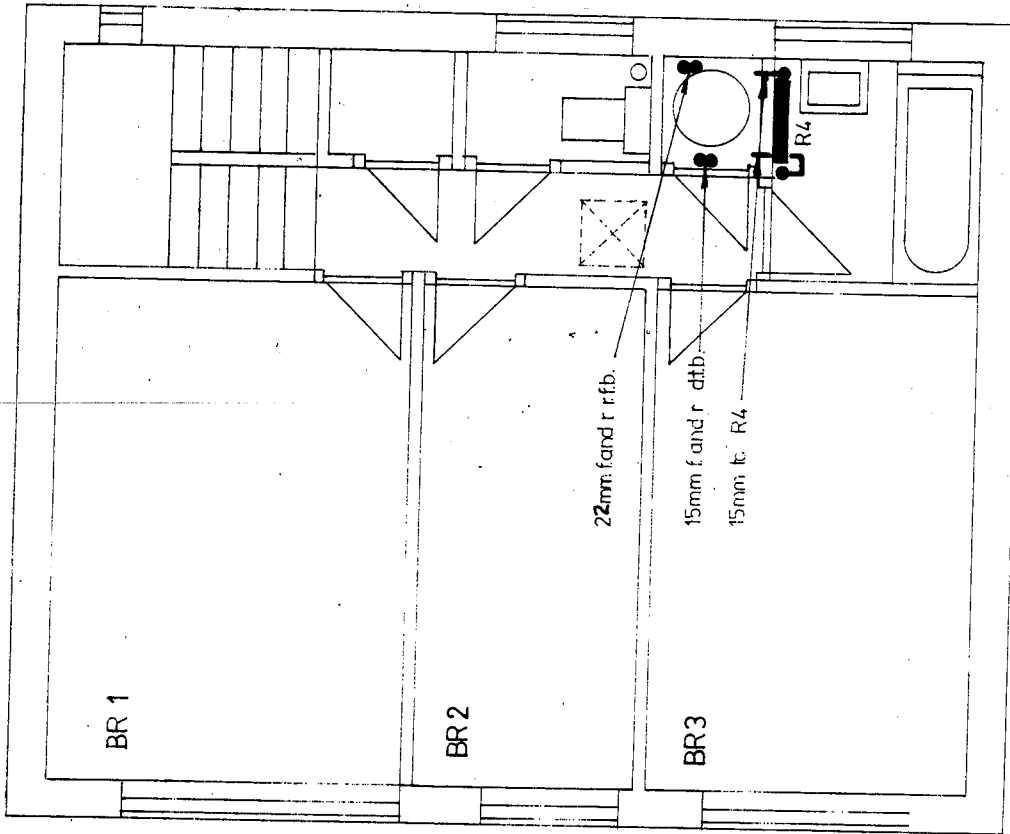


First floor

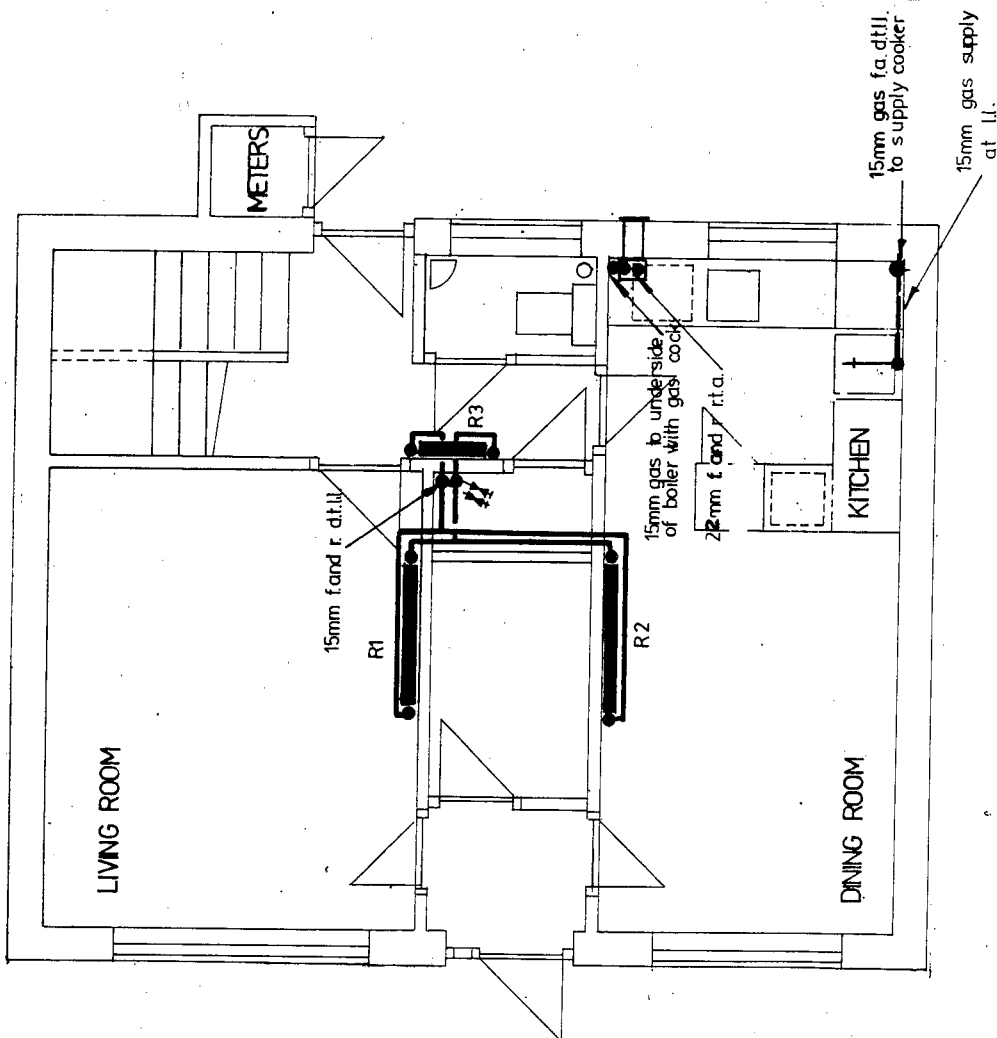


PENNYLAND DUAL ASPECT HOUSE - PLANS & RADIATOR POSITIONS
FIGURE 13.

First floor



Ground floor



PENNYLAND SINGLE ASPECT
PUMPS & RADIATOR POSITIONS

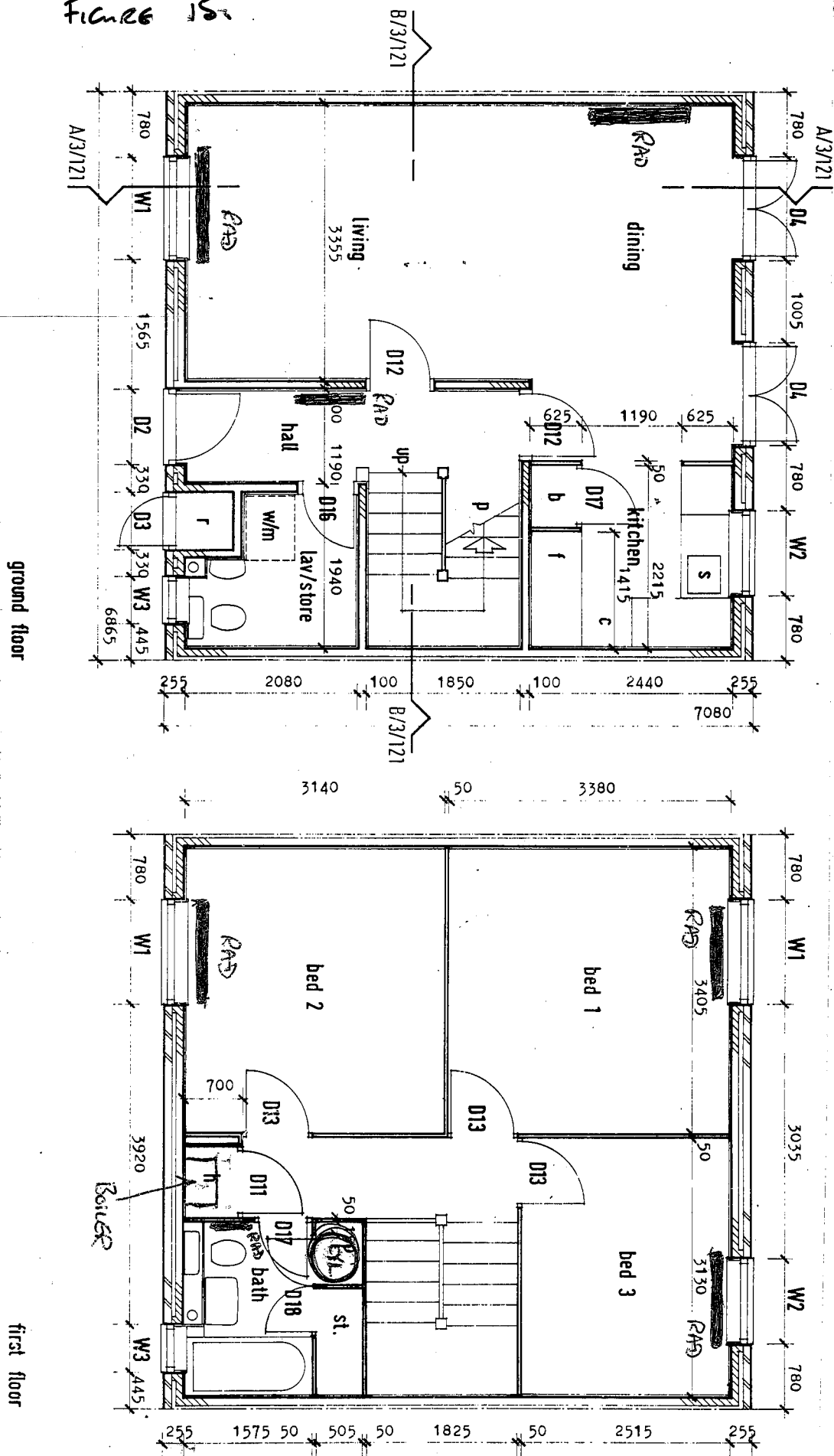
FIGURE 14.

Neath Hill houses

Figures 15 to 23 show floor plans, typical cross-sections, elevations and window details for the Neath Hill houses. The 18 houses monitored in the experiment included two basic types, 5A and 5C. These have the same approximate floor area, but the type 5A houses have a long frontage facing the street with a correspondingly shallow plan, and type 5C houses have a narrow frontage with a deep plan. Two of the deep plan houses have a 'splayed' layout to allow a 20° turn to be put into the terrace. The meaning of this will be obvious from the floor plans.

Figures 15 and 17 show the radiator positioning. Not all of the houses were equipped with radiators upstairs, only those designated 'high specification'. The boiler was located, together with the heating timeclock in an upstairs cupboard, with a flue extending up through the roof and an air intake to the loft space. The pipework distribution was through the intermediate floor.

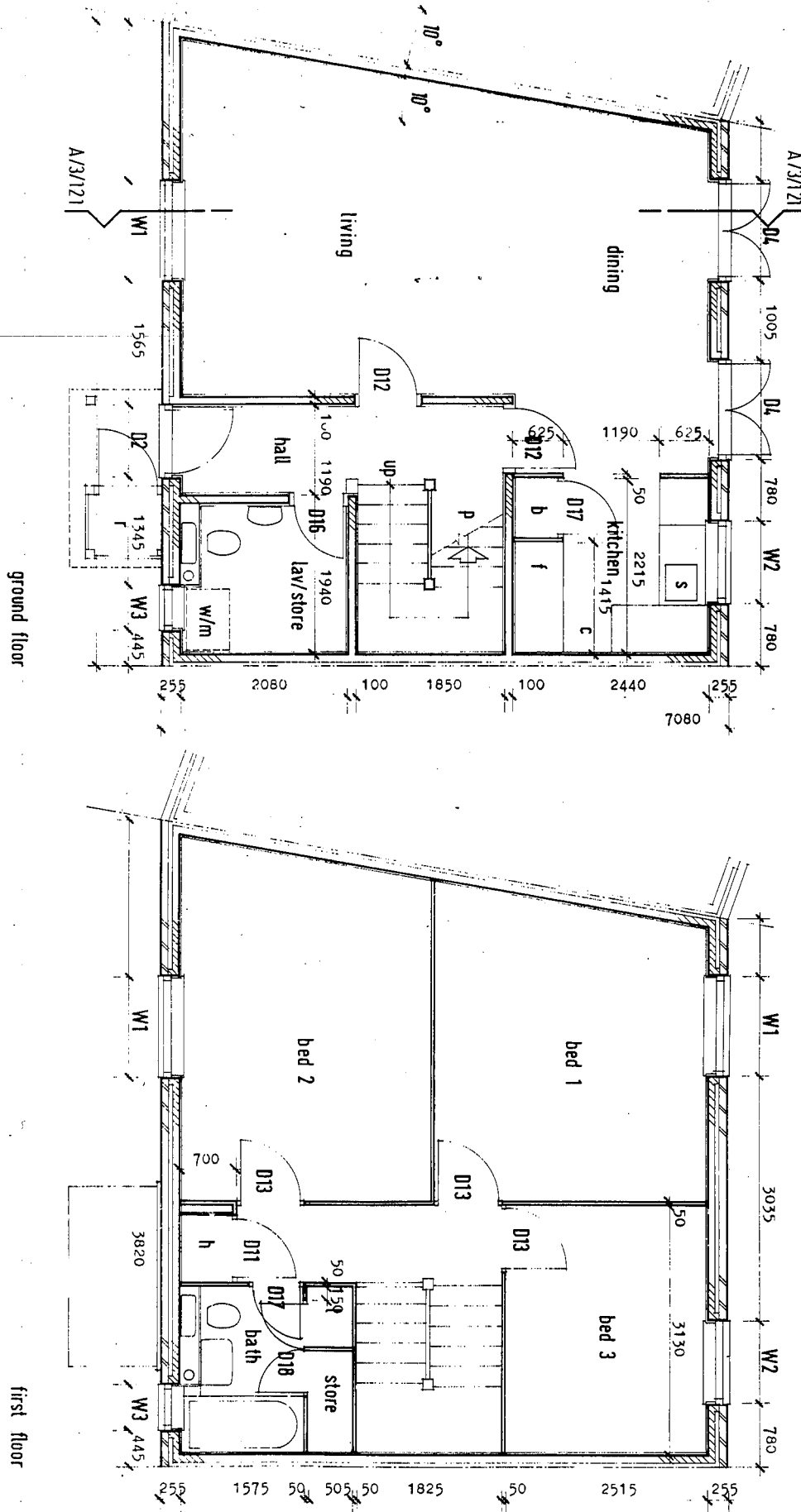
Figure 15.



upstairs RAD, STAIRS ONLY IN HIGH-SPEC HOUSES

Neath Hill deep plan (5C) floor plans

FIGURE 16



Neath Hill "splayed" deep plan house

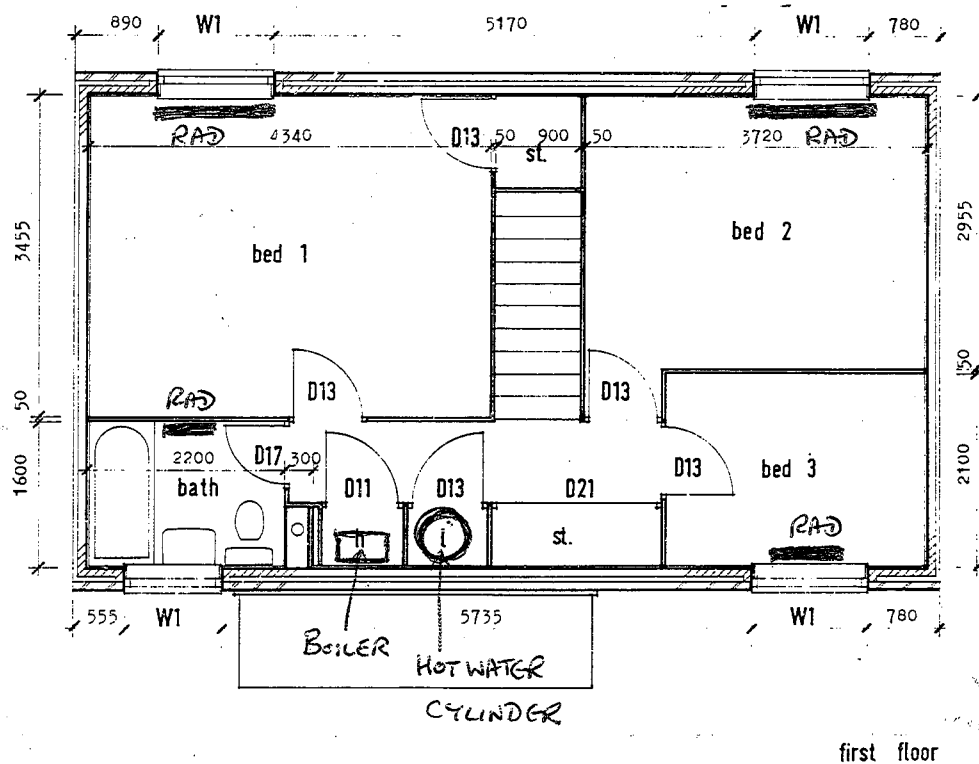
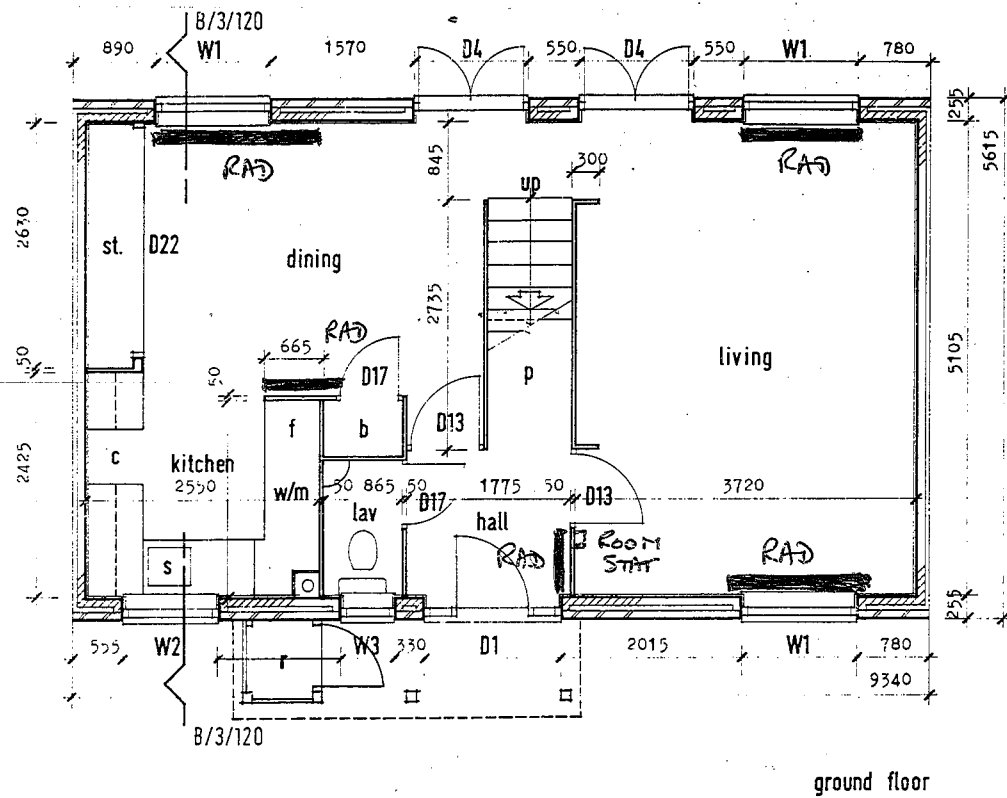


FIG. 17

Neath Hill shallow-plan (5A) floor plans
 UPSTAIRS RADIATORS ONLY IN HIGH-SPECIFICATION HOUSES

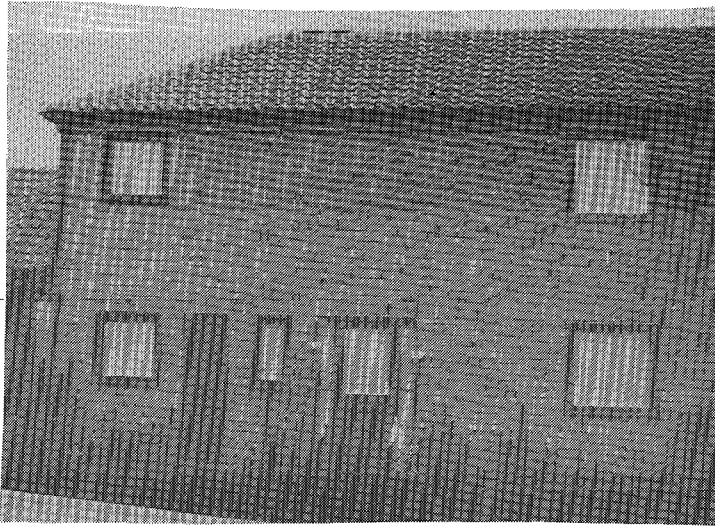


Figure 18 Shallow plan front facade



Figure 19 Deep plan front facade



Figure 20 Shallow plan rear facade

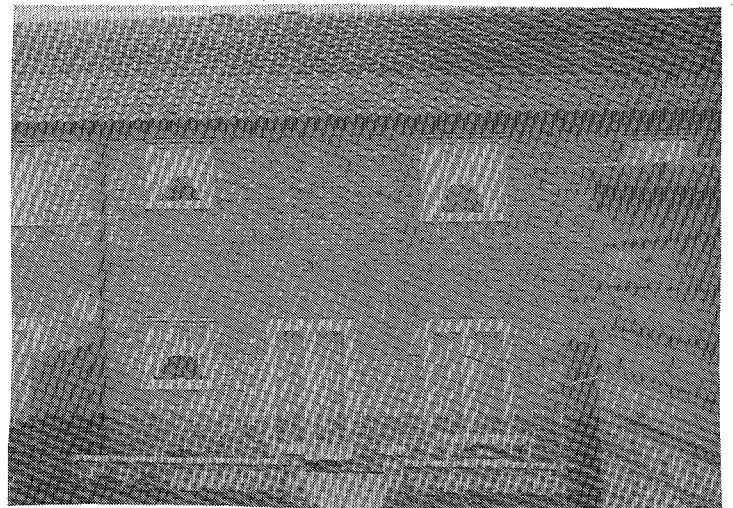


Figure 21 Deep plan rear facade

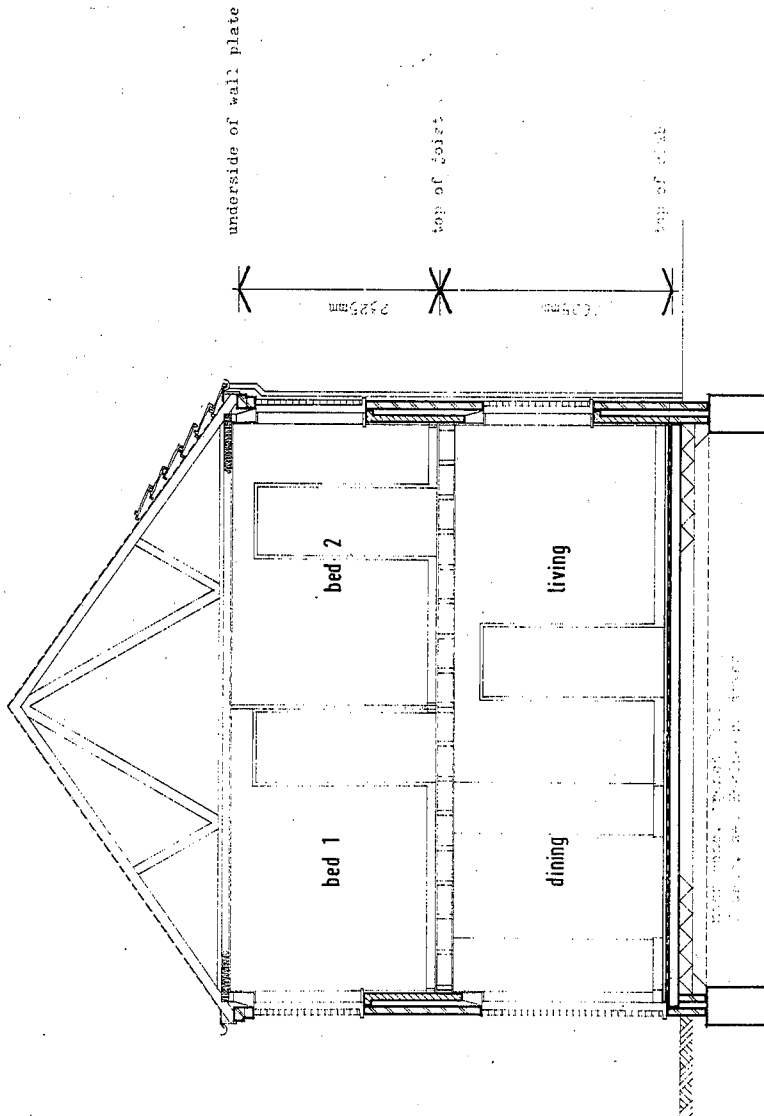
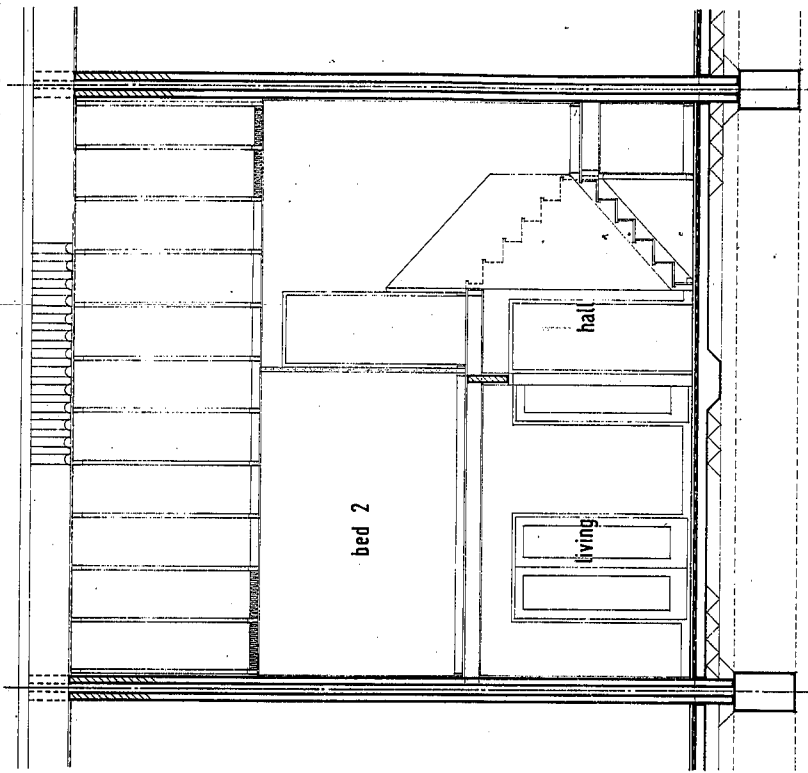
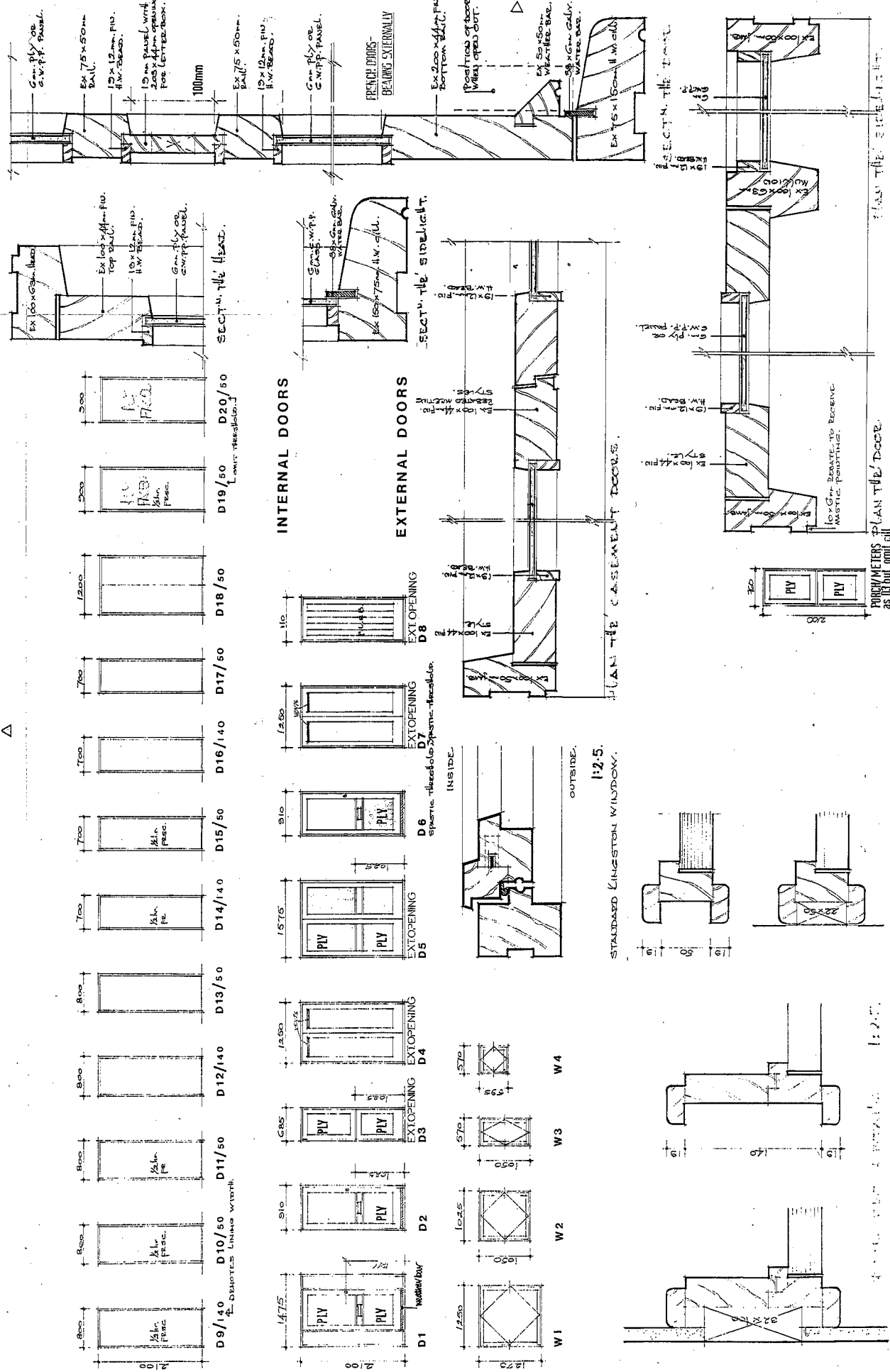


FIG 22 TYPICAL CROSS-SECTION OF NEATH HILL
DEEP-LAN HOUSE



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Project	Drawn	Checked	Project no.	Source ref.
Neath Hill (site 5) housing	GS		P 60/098	
Drawing title	Date	Scale	Drawing no.	Revision
Typical Section	June '76	1:50	3/121	



10534345

Milton Keynes Development Corporation
Warrington Town, Warrington, Milton Keynes MK17 8LX
Telephone: Milton Keynes 7800

Project: NEATH HILL (SITE 5) RESIDENCE, G.A.T.
Drawing title: WINDOW & DOOR DETAILS
Drawing no.: 4/1/1
Scale: 1/10
Date: 1/1/1
Revision: 1

FIG 23. NEATH HILL WINDOW & DOOR TYPES & DETAILS.

APPENDIX 4

STANDARD U-VALUES AND HEAT LOSSES

APPENDIX 4: Standard U value and heat losses for Pennyland and Neath Hill

4.1. Summary

Fabric heat loss coefficients for the houses at Pennyland and Neath Hill can be estimated from the IHVE guide book, and the plans and elevations of the houses. This has been done for all the 5 person houses that were involved in the project, and the following comments are in order:

1. The fabric heat losses of the houses depend strongly on the degree of terracing of the houses. At Pennylands terraces are often staggered and there are both single and two storey houses. In order to represent this complexity, we have identified 8 levels of terracing, ranging from a terrace level of 0 for a detached house to a level of 8 for a mid terrace house. The way this works is shown in Figure A.4.1.
2. The fabric heat loss coefficients of the Pennyland and Neath Hill houses are affected by the depth of the plan. At Pennyland long shallow houses have been chosen to carry the passive solar measures, because the long frontage makes it easier to concentrate the glazing on one side. The short deep variant is therefore (relatively) non-passive. These house types are usually referred to as single and dual aspect respectively. It is important to remember therefore, that the solar houses at Pennyland have a slightly higher average fabric heat loss than the non-solar houses.

While there are two distinct house types at Neath Hill (5A which is shallow plan and 5C which is deep plan) neither is associated with passive solar design features. These points are all illustrated in the following table:

Fabric heat losses (5 person houses) W/K		
	mid terrace	end terrace
Neath Hill 5A	178	201
Neath Hill 5C	137	165
Pennyland 1 single	166	193
Pennyland 1 dual	140	171
Pennyland 2 single	112	129
Pennyland 2 dual	96	115

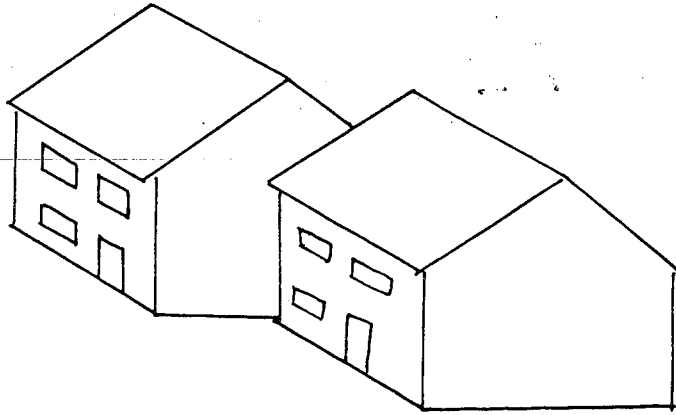
The fabric heat loss coefficients of the houses at Neath Hill and Pennyland effectively form a continuum, from about 95 W/K for mid terrace dual aspect houses at Pennyland 2, to about 200 W/K for detached houses at Pennyland 1. It is important to realise that although we often speak of the three groups of houses as providing two clearly different levels of insulation, (1982 regulations and a higher standard) this is not in fact the case. For example the worst of the Pennyland 2 houses (in this respect) are only about 10 W/K better than the best of Pennyland 1. Figures A.4.2 - 5 show histograms of the fabric heat

A.4.2.

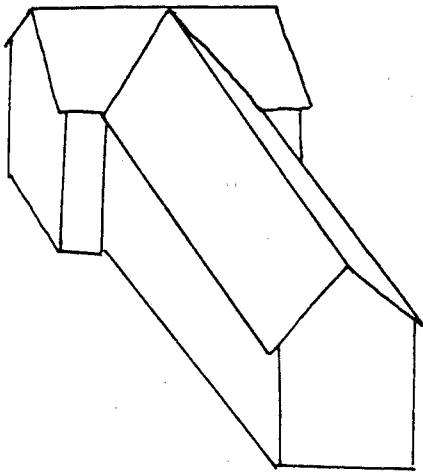
loss coefficients for all 5 person houses on the three estates (a total of 139) to illustrate this.

Finally it is important to remember that the infiltration rates are probably more than twice as high at Neath Hill as at Pennyland. Variations in ventilation rates will add to the spread of whole house heat loss coefficients within each group and the systematic difference between Neath Hill and Pennyland will widen the gap between these two groups of houses by some 20 to 30 W/K.

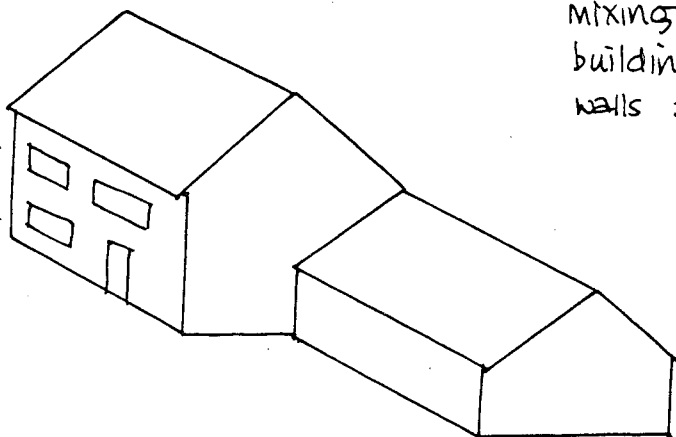
Figure A.4.1: Illustrating different degrees of terracing



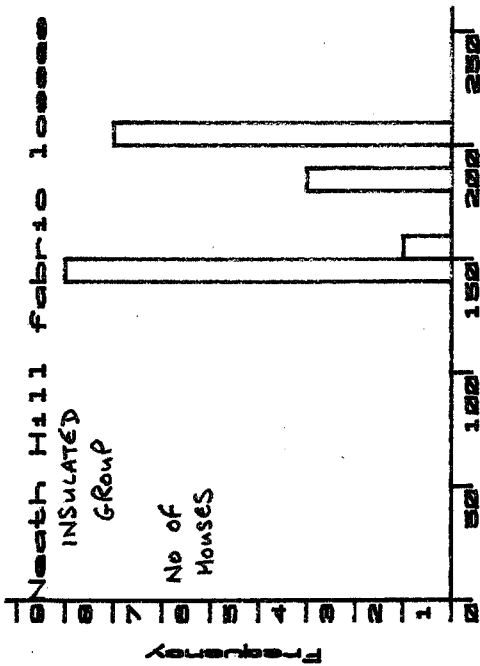
horizontal staggering leads to some end walls being half exposed.



mixing single and dual aspect houses in terraces leads to some end walls being three-quarters exposed



Mixing single and two storey buildings leads to some end walls being one quarter exposed



W/K FIG. A.4.2.

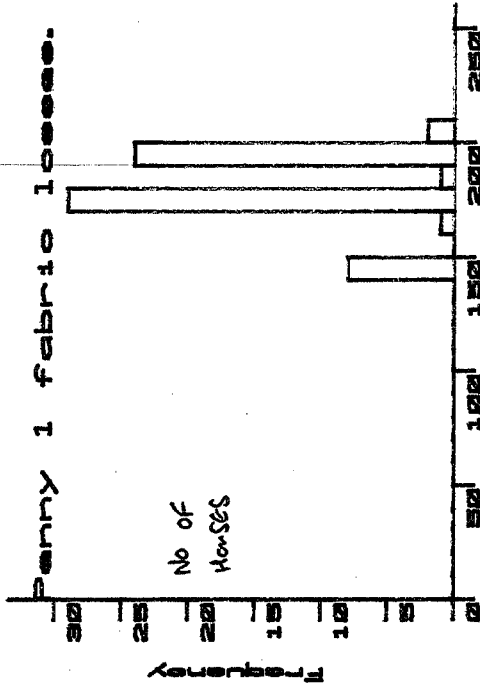


FIG. A.4.3.

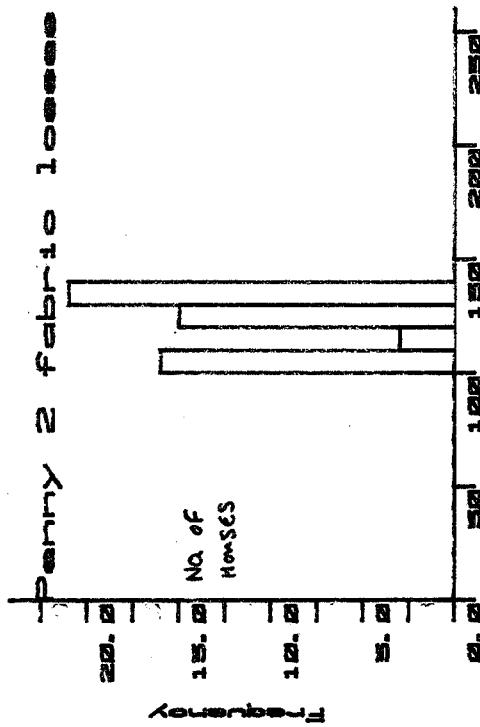


FIG. A.4.4.

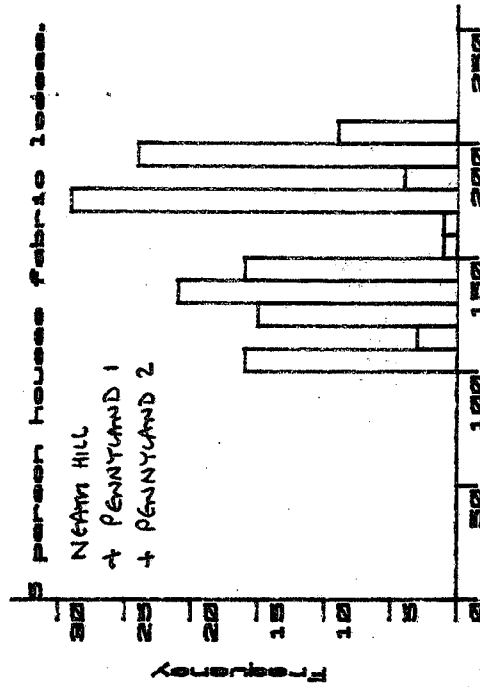


FIG. A.4.5.

4.2. Introduction

The following contains estimates based on the IHVE guide book part A.3, (1970 edn.) for the U values of all significant building elements and estimates of the whole house heat loss coefficients for the Pennyland and Neath Hill houses. There are two insulation levels at Pennyland (high and moderate) and two at Neath Hill (the 18 houses monitored as part of the Pennyland project, which are nominally the same as the moderate level at Pennyland, and the rest of the Neath hill houses, which were built to the 1975 building regulations).

References are included to the highly insulated houses at Great Linford where appropriate, though these houses are not treated in detail here.

4.3. Standard U values and heat losses at Pennyland

Lofts

The highly insulated houses at Pennyland have 140 mm insulation over most of the first floor ceiling laid between joists, with the joists forming a cold bridge. The Great Linford houses are almost identical in construction, with a nominal 150 mm of insulation between the joists. The difference in U value will be of the order of 5%. This results in the following U value:

Pennyland high insulation and Linford		
	k value	resistance
fibreglass 140 mm	0.040	3.50
6% 35x100 mm joists	0.13	0.77
resulting resistance	-	2.89
loft space	-	0.18
internal surface R	-	0.22
plasterboard 12 mm	0.16	0.08
total resistance		3.37
U value		0.30

The moderately insulated Pennyland 1 houses have 80 mm of insulation over the whole of the first floor ceiling. This level of insulation has also been applied to a strip approximately 0.3 m wide next to the eaves in the highly insulated houses at Pennyland area 2. This results in the following U values:

A.4.6.

Pennyland moderate insulation		
	k value	resistance
fibreglass 80 mm with 6% 35x100 mm joists	-	1.94
resistance of loft space	-	0.18
internal surface R	-	0.22
plasterboard 12 mm	0.16	0.08
total resistance		2.42
U value		0.41

The effect of the cold bridging by the joists is quite important in these houses. If the insulation in the Pennyland 2 houses had been laid part between and part over the joists, the U value of the flat part of the roof would have been about 0.27 rather 0.30.

Walls

This section presents estimates for the U values for walls for the moderately and highly insulated houses at Pennyland. The latter are very similar in expected U values (if not in construction) to the walls in the houses at Great Linford. A table for the Linford houses has been included for completeness. Note that we have not taken into account cold bridging by wall ties, lintels or cavity returns at doors and windows.

Pennyland moderate insulation		
	k value	resistance
brick 100 mm	0.81	0.124
insulation 50 mm	0.04	1.25
dense concrete 100 mm	0.88	0.114
internal surface	-	0.123
external surface	-	0.06
total resistance		1.67
U value		0.60

A.4.7.

Pennyland high insulation		
	k value	resistance
brick 100 mm	0.81	0.124
fibreglass 100 mm	0.04	2.50
dense concrete 100 mm	0.88	0.114
internal surface	-	0.123
external surface	-	0.06
total resistance		2.92
U value		0.34

Linford		
	k value	resistance
brick 100 mm	0.81	0.124
insulation 100 mm	0.04	2.50
dense clincker block 100 mm	0.43	0.24
plaster 12 mm	0.5	0.02
internal surface	-	0.123
external surface	-	0.06
total resistance		3.07
U value		0.33

Floors

Floors are not well understood, and are particularly problematic at Pennyland because their very long time constants make analysis of energy consumption data rather messy. The values we have actually measured at Linford suggest that the IHVE guide may under estimate floor heat losses, and moreover, that heat losses may be affected by such factors as very heavy rain. C'est la vie.

Pennyland high insulation: floor U values	
terraced	0.34
detached	0.57
end of terrace	0.46

A.4.8.

Pennyland moderate insulation: floor U values	
terraced	0.45
detached	0.76
end of terrace	0.61

These figures can be compared with the value estimated for floors in the Great Linford houses (see Everett et al 1984) of 0.57.

Doors and windows

I have used IHVE standard U values for complete windows with 30% wooden window frame in sheltered locations. Doors are all single glazed with single skin plywood panels at Pennyland and are assumed to have the same U value as a single glazed window. At Linford the front door is single glazed but of fairly thick wood, and the back door is double glazed using sealed units with a 6 mm air gap. Both are assumed to have a U value equivalent to that of a double glazed window.

double glazed windows	2.5
single glazed window	4.3
Pennyland doors	4.3
Linford doors	2.5

4.3.1. Areas of building elements

On Pennyland there are three basic types of five person 3 bedroom houses, respectively 5pD, 5pE, and 5pF. The first two of these are dual aspect houses which differ only very slightly. The third is a single aspect house, the "passive solar variant". Superimposed on these three types are two insulation levels, corresponding to current building regulations, and a higher standard. This section sets out the areas of all significant building elements in the three basic house types. Conventions used here are:

1. Dimensions of walls, floors and ceilings are means of external and internal dimensions.
2. Window dimensions are overall dimensions, including frames.

Dimensions and the labelling of doors and windows have been taken from the plans and elevations, and window schedules that are presented in appendix 3.

5 pD terraced

Window areas m ² . 5pD		
W10	1.90	
W13	0.20	
W5	3.37	south
W10	1.90	
W12	0.68	
W9	2.53	south
W11	1.27	south
total area	11.9	
south facing	7.2	

Summary of areas. 5pD	
gross area of wall	65.1
net area of wall	49.4
area of windows	11.90
area of doors	3.78
area of floor	49.14
area of ceiling: flat	43.5
area of ceiling: sloping	5.7

Notes

1. Wall area includes reentrant feature near door.
2. Floor area includes exposed floor of bedroom 3 above reentrant door.

5pE terraced

Window areas m ² . 5pE		
W2	3.88	south
W10	1.90	
W13	0.20	
W9	2.53	south
W11	1.27	south
W10	1.90	
W12	0.68	
total area	12.36	
south facing	7.68	

Summary of areas. 5pE	
gross area of wall	65.1
net area of wall	49.0
area of window	12.36
area of doors	3.78
area of floor	49.14
area of ceiling: flat	43.5
area of ceiling: sloping	5.7

Notes

1. Effects of reentrant door are included as for 5pD houses.

5pF terraced

Window areas m ² . 5pF		
W2	3.88	south
W3	2.91	south
W12	0.68	
W11	1.27	
W9	2.53	south
W11	1.27	south
W10	1.90	south
W1	0.62	
W12	0.68	
W12	0.68	
total area	16.42	
south facing	12.49	

Summary of areas. 5pF	
gross area of wall	78.0
net area of wall	57.3
area of windows	16.4
area of doors	4.25
area of floor	49.14
area of ceiling: flat	42.1
area of ceiling: sloping	7.0

A.4.11.

The clear glass fraction of the windows at Pennyland is about 0.7 in the moderately insulated houses, and about 0.85 in the highly insulated houses. This discrepancy is due to the fact that there are a lot more glazing bars in the single glazed windows of the moderately insulated houses than in the "sashless" double glazed windows in the highly insulated houses.

It is worth noting that the back doors of the dual and single aspect houses at Pennyland are glazed. This adds about 2.4 m² to the area of south facing windows in the single aspect houses and about 1.9 m² in the case of the 5pE houses. The clear glass fraction of these doors is about 0.5 which is considerably less than the clear glass fraction of the windows, especially in the highly insulated houses. The front doors of the Pennyland houses are partly glazed, adding about 0.6 m² of clear glass to the total area of south facing glass in the case of the 5pD houses.

This area is however heavily shaded, and probably does not add significantly to the effective solar aperture of these houses.

The resulting south facing clear glass areas are shown in the table below:

South facing clear glass areas at Pennyland		
	high	moderate
5pD	6.1	5.0
5pE	7.5	6.3
5pF	11.8	10.0

The fact that the glazed areas are higher in the highly insulated houses probably slightly more than cancels the additional transmissions losses in the double glazed windows in these houses compared with the moderately insulated houses.

4.3.2. Fabric heat losses

Fabric losses calculated on the basis of the element areas and U values presented above, are as follows:

5pD terraced. W/K		
	High	Moderate
walls	16.8	29.6
windows	30.1	51.2
doors	16.3	16.3
roof	15.4	20.1
floor	16.6	22.1
total	95.2	139.2

Note in highly insulated houses, all windows except W1 and W13 and glazing associated with the doors are double glazed.

5pE terraced. W/K		
	High	Low
walls	16.7	29.4
windows	31.3	53.2
doors	16.3	16.3
roof	15.4	20.1
floor	16.6	22.1
total	96.3	141.0

5pF terraced. W/K		
	High	Low
walls	19.5	34.4
windows	42.2	70.6
doors	18.3	18.3
roof	15.5	20.1
floor	16.7	20.1
total	112.2	165.5

4.3.3. Corrections for additional end walls

All heat loss calculations so far assume mid terrace houses. End of terrace and detached houses have higher whole house heat loss coefficients. These may be calculated roughly using the following tables. Note that the treatment of extra floor heat loss through exposed end walls in the rest of the report, which is based on the tables below, could be improved.

Dual aspect houses: addition per exposed end wall W/K		
	High	Low
wall ($\text{del}(A) \times U$)	13.3	23.4
floor ($A \times \text{del}(U)$)	5.9	7.9
total ($\text{del}(A \times U)$)	19.2	31.3

A.4.13.

Single aspect houses: addition per exposed end wall W/K		
	High	Low
wall ($\Delta(A) \times U$)	10.7	18.9
floor ($A \times \Delta(U)$)	5.9	7.9
total ($\Delta(A \times U)$)	16.6	26.8

Effects due to increased wall areas are larger by perhaps a factor of 2 than the effects due to increased floor heat loss. This is comforting in view of the uncertainties in the latter.

4.3.4. Summary of heat loss coefficients: Pennyland terraced houses

The fabric heat loss coefficient in the above are summarised in the tables below. Also included here are ventilation heat losses, based on ventilated house volumes at 3 different air change rates. The ventilated volume of all 3 house types is 216 m³, not allowing for the volume of internal partition walls.

Fabric losses		
W/K	High	Low
dual aspect	96	140
single aspect	112	166

Addition for end of terrace houses		
W/K	High	Moderate
dual aspect	19	31
single aspect	17	27

Ventilation losses	
ACH	W/K
0.25	18
0.5	36
1.0	72

Whole house heat losses at 0.5 ACH		
W/K	High	Low
dual aspect	132	176
single aspect	148	202

4.4. Standard U values and heat losses at Neath Hill

Insulation levels of lofts, walls, windows and doors and floors in the 18 houses on Neath Hill are nominally to the same standard as Pennyland area 1. In practice, the 50 mm cavities in the walls are insulated with urea-formaldehyde foam in Neath Hill, as opposed to rock wool on Pennyland area 1. This may lead to a difference in the in-situ U values of the walls between the two nominally identical estates. No measurements of the U values of either set of walls have been carried out. The sensitivity of the whole house heat loss coefficients on Neath Hill to a plausible upward variation in wall U value is therefore investigated.

4.4.1. Standard U values

The U values of building elements at Neath Hill have been assumed to be the same as those of the corresponding elements of the moderately insulated Pennyland 1 houses. These U values are summarised below:

U values at Neath Hill	
lofts	0.41
walls	0.60
doors and windows	4.3
floors: terraced	0.45
floors: end of terrace	0.61

4.4.2. Areas of building elements

On Neath Hill there are two basic house types, 5A and 5C. These are deep and shallow plan terraced houses respectively. Six of the houses have full house central heating, and two are not rectangular in plan, as they occupy a position at the apex of a 20 degree kink in a terrace of houses. All of these details may be seen on the plan of the estate and the plans and elevations of the houses which are presented in appendix 3 of this report. The labelling of the doors and windows is based on the window and door schedule presented in appendix 3. Conventions for calculation of areas used here are the same as were used in the first half of the present appendix.

5A terraced

Window and door areas m ² . 5A	
7 x W1	11.2
W2	1.08
W3	0.60
D1	3.1 (opaque)
2 x D4	5.25
total	21.2

Notes

The two D4 doors in the above are french windows in the living area of the house. The door D1 is a plywood panelled front door.

Summary of areas. 5A	
gross area of wall	93.4
net area of wall	72.2
area of windows and doors	21.2
area of floor	50.1
area of ceiling	50.1

5C terraced

Window and door areas m ² . 5C	
3 x W1	4.77
2 x W2	2.16
2 x W3	1.20
D2	1.91
2 x D4	5.26
total	15.3

Summary of areas. 5C	
gross wall area	68.7
net wall area	53.4
area of windows and doors	15.3
area of floor	45.6
area of ceiling	45.6

5C terraced splayed

The two splayed 5C houses are identical to standard 5C houses except for one party wall, which is opened out by 10 degrees. Window and door details are unaltered. These two houses have whole house central heating, while the standard 5C houses have radiators downstairs only. These houses are denoted by 5CHS to indicate the splaying, and the changes to the heating system.

Window and door areas m ² . 5CHS	
3 x W1	4.77
2 x W2	2.16
2 x W3	1.20
D2	1.91
2 x D4	5.26
total	15.3

Summary of areas. 5CHS	
gross wall area	74.9
net wall area	59.6
area of windows and doors	15.3
area of floor	49.7
area of ceiling	49.7

4.4.3. Fabric heat losses

5A terraced. W/K	
walls	43.3
windows and doors	91.2
roof	20.5
floor	22.6
total	177.6

5C terraced. W/K	
walls	32.0
windows	65.8
roof	18.7
floor	20.5
total	137.0

5CHS terraced. W/K	
walls	35.8
windows and doors	65.8
roof	20.4
floor	22.4
total	144.4

4.4.4. Corrections for additional end walls

All heat loss calculations so far assume terraced houses. End of terrace and detached houses have higher whole house heat loss coefficients. These may be calculated using the following tables.

5A: addition per exposed end wall W/K	
wall ($\text{del}(A) \times U$)	14.7
floor ($A \times \text{del}(U)$)	8.0
total ($\text{del}(A \times U)$)	22.7

5C: addition per exposed end wall W/K	
wall ($\text{del}(A) \times U$)	20.5
floor ($A \times \text{del}(U)$)	7.3
total ($\text{del}(A \times U)$)	27.8

Effects due to increased wall areas are larger by perhaps a factor of 2 than the effects due to increased floor heat loss. This is comforting in view of the uncertainties in the latter.

4.4.5. Sensitivity to wall U value

As stated above the U values of the walls of the Neath Hill houses is uncertain and may be greater than the value of 0.60 used above. The table below shows the increases in the whole house heat loss coefficients of the three types of houses which would result if the actual U value of the walls were 0.80. Since the U value of an uninsulated wall built to 1975 regulations is 1.0, this may be taken to be a likely upper limit. These values will be increased for end of terrace houses.

Effect of wall U value increase by 0.2 W/m ² /K. W/K		
	5A	14.4
	5C	10.6
	5CHS	12.0

4.4.6. Summary of heat loss coefficients: Neath Hill terraced houses

The fabric heat loss coefficients estimated in the above are summarised in the tables below. The ventilated volumes of the 3 house types are shown below. These figures do not allow for the volume of internal partition walls, floors, or fittings. Infiltration rates at Neath Hill are at least double those at Pennyland (see appendix 7). We have therefore evaluated the whole house heat loss coefficients for Neath Hill at 1 ACH rather than the 0.5 ACH used for Pennyland.

Volumes of Neath Hill houses m ³		
	5A	232
	5C	217
	5CHS	237

Fabric heat losses W/K		
	mid terrace	end terrace
5A	178	201
5C	137	165
5CHS	144	-

Ventilation losses at 1 ACH. W/K		
	5A	77
	5C	72
	5CHS	79

Whole house heat losses at 1 ACH. W/K		
	mid terrace	end terrace
5A	255	278
5C	209	237
5CHS	223	-

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For immediate comparison, we show below the whole house heat loss coefficients of the Pennyland area 1 houses.

Whole house heat losses at 0.5 ACH. W/K		
	mid terrace	end terrace
dual aspect	176	207
single aspect	202	229

Neath Hill uninsulated houses

For completeness, fabric heat losses for the Neath Hill uninsulated houses are included here.

Fabric heat losses W/K		
	mid terrace	end terrace
5A	207	240
5C	158	200
5CHS	168	210

APPENDIX 5

DIFFERENTIAL TEMPERATURE INTEGRATOR

Article reproduced from 'Wireless World' magazine,
March, 1984.

Differential temperature integrator

Battery-powered remote-reading integrating thermometer has application in energy-conservation schemes

As much as 25% of the UK's primary energy consumption is in domestic buildings, yet relatively little is known about the details of its use. Individual tastes vary wildly and variations of annual energy consumption of 3:1 or more between identical houses are quite common. Because of this, testing out some new insulation measure or heating system requires monitoring a large number of houses. This can be a very expensive business.

The traditional instrument for temperature recording has been the thermograph, a kind of clockwork chart recorder, still to be seen ticking away in the corners of art galleries and museums. More recently memory-based electronic recorders have appeared that can be read out into a computer.

For most housing work all that is re-

R. Everett

quired are weekly or monthly averages of temperature plus the opportunity to sample spot values, such as the evening living-room temperature. Most importantly, this must be done without disturbing the house occupants and without spending vast sums on cabling back to a central datalogger. The differential temperature integrator was specifically developed for the Pennyland field trial in Milton Keynes, one of many sponsored by the UK Departments of Environment and Energy in recent years, and involved monitoring 80 houses of varying insulation level and south-facing window area¹.

Why a 'differential' integrator?

The heating energy consumption of a house is roughly proportional to the average inside-outside temperature difference (ΔT), the constant of proportionality being an indication of the insulation level of the house. To evaluate the effectiveness of insulation, weekly heating energy consumption needs to be correlated with weekly ΔT . We can extend the process to include solar radiation to make an estimate of the 'passive' solar gains into a house. ('Passive' as opposed to the 'active' solar energy that you get from solar panels.)

As various zones of a house are at different temperatures, a weighted average of

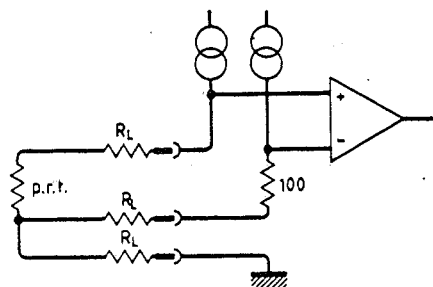
the different temperatures of different rooms is required. Thus the job of the d.t.i. is simply to generate cumulative integrals of the difference in temperature between each of three sensors inside the house, two downstairs and one upstairs, and a fourth on the outside, preferably on the north side out of the sun's rays. The temperatures are sampled every 8 minutes and the cumulative integrals are clocked up on three liquid-crystal displays, in units of degree-days (i.e. 1degC for one day, commonly used in building work). For the Pennyland field trial the integrator was mounted alongside the gas and electricity meters in an external meter cupboard where it could be read by the researchers without entering the house. The d.t.i. also has a hold mode allowing any of the four temperatures to be sampled on a test point with a d.v.m.

This device is a logical solution to a monitoring problem; I was not surprised therefore to find a paper proposing such a device after completing the prototype².

Circuit design

The temperature sensors used are thin-film platinum resistance types (such as RS 158-238), effectively precalibrated to $\pm 0.3\text{degC}$. This type of sensor has a resis-

Designed for temperature monitoring in energy conservation field trials at Milton Keynes this thermometer provides weekly average temperature differences between each of three zones of a house and the outside air temperature. Put crudely, heating energy consumption to a house is proportional to the temperature difference and the constant of proportionality is a measure of the quality of house insulation. The device requires three platinum resistance thermometers installed in the house, nominally one each in living room, kitchen and a bedroom, and an outside air temperature sensor. These four sensors are wired to the integrator box located in some convenient place, such as a meter or bin cupboard on the outside of the house, where it can be read weekly along with gas and electricity meters without disturbing the house occupants.



Note: Positions of heat meters may vary from house to house

Fig. 1. Three-wire bridge circuit puts equal lead resistance in each arm, with one lead in common.

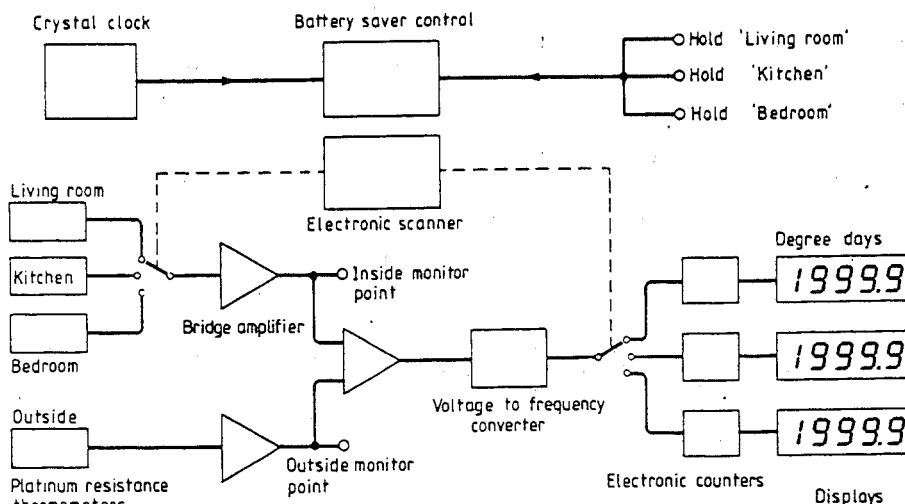
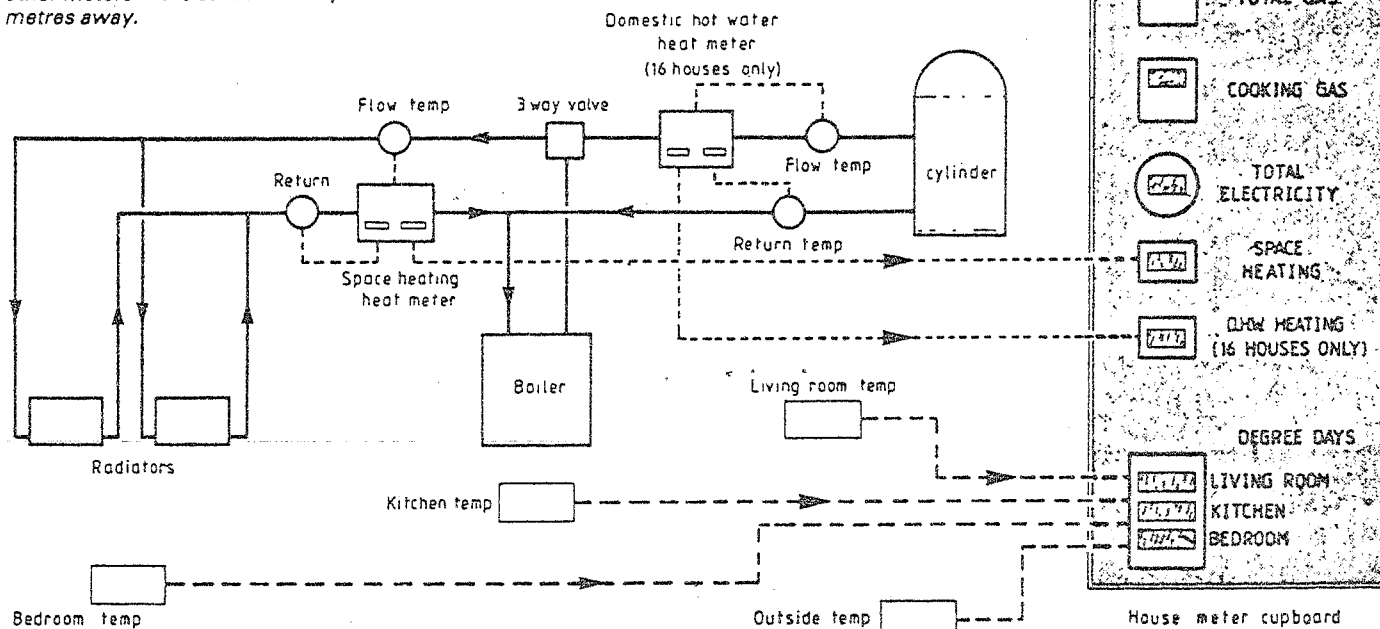


Fig. 2. Battery-saving circuitry samples temperatures every few minutes - the amplifier and v. to f. converter are multiplexed between sensors.

Fig. 3. Temperature integrator is mounted in the house external meter cupboard with other meters — the sensors are up to 10 metres away.

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tance of 100 ohms at 0°C rising to 138.5 ohms at 100°C.

Because lead resistances are likely to be significant it is usual to use them in a bridge arrangement, as in Fig. 1. Here the p.r.t. is compared with a precision 100 ohm resistor (e.g. RS158-086) and the bridge ensures that equal lead resistances appear in each arm, with one resistance in common.

I wouldn't recommend the use of i.c.

constant-current sources in this type of bridge. Many have large temperature coefficients (read the fine print for long-term drift characteristics!) and more than one is sold as a dual-purpose constant-current source/temperature sensor! More recently, precalibrated thermistors have become available cheaply and these are now a better choice for temperature measurement than p.r.t.s because of their higher output.

The temperature integration process is

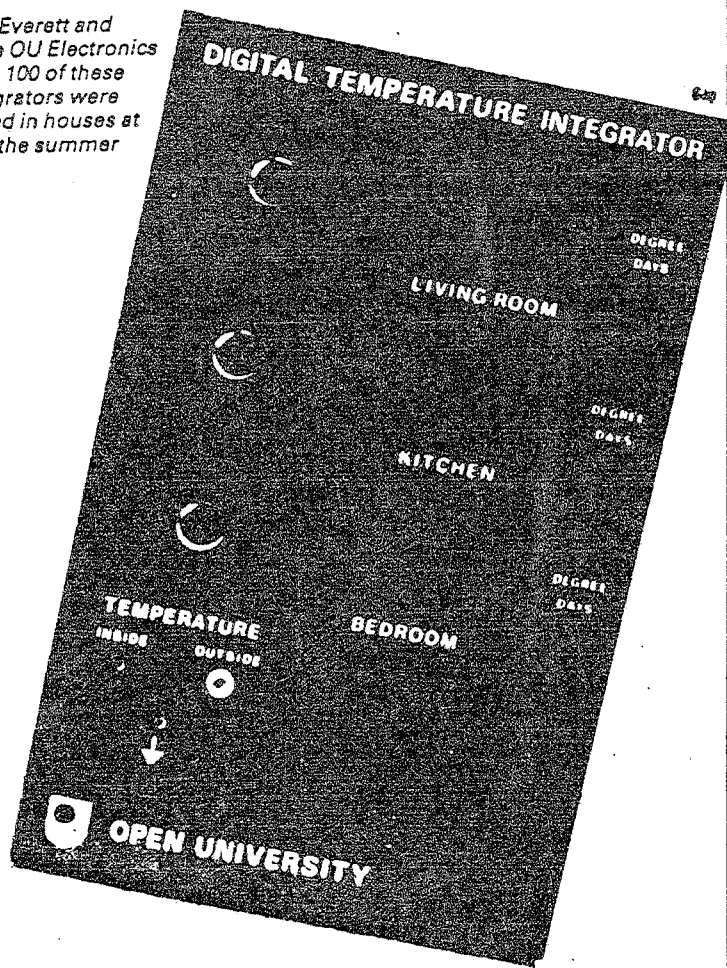
achieved by feeding the difference between the inside and outside temperatures to a voltage-to-frequency converter and then counting and displaying the resulting pulses. To minimize drift, the bridge amplifiers are ICL7600 commutating auto-zero types. To keep the component-count down the internal temperatures are multiplexed into a single bridge amplifier and v-to-f converter (see block diagram).

Much of the circuitry is devoted to battery saving. This allows four D-size and six AA-size alkaline cells to last up to six months.

The 32.768kHz crystal oscillator is counted down by 4040 counters and decoded with the 4068 and gate to wake up the sleeping system for two seconds in 512 (about eight minutes). In the off state, battery consumption is essentially that of the three liquid crystal displays (about 300µA). The circuit cycles through four phases of 500ms each, starting with a settling period with the amplifier inputs grounded. Then each of the sensors in turn is routed through the input multiplexer and the bridge amplifier to the v-to-f converter. The resulting pulse train is routed to the appropriate 4040 counter and 7224 counter/display driver.

The v-to-f converter (Teledyne 7400 or RS307-070) requires a stabilized negative voltage rail as a reference, the stability of

Designed by Bob Everett and engineered by the OU Electronics Common Facility, 100 of these temperature integrators were made and installed in houses at Milton Keynes in the summer of 1981.



Bob Everett is currently a Research Fellow in the energy research group of the Open University. He studied mechanical and electrical engineering at Cambridge University, graduating in 1970, and subsequently worked on computer phototypesetting development for the (then) International Publishing Corporation. Since 1976 he has worked on a number of solar energy projects in Milton Keynes. He is embarrassingly fond of his ZX81.



◀ **Fig. 4.** Light-emitting diode and associated switches were included for production testing and could be omitted. The l.e.d. was an idea to set the v. to f. converter gain without an oscilloscope by beating the output against the crystal clock, but the 'scope is a lot easier in practice.

the positive rail being not nearly so critical. Hence the use of a 9V battery regulated to 5V to drive v-to-f converter, bridge amplifiers and the bridge.

Pressing any one of the individual hold buttons powers the system. The 4532 priority encoder selects the appropriate two-bit address and also allows the normal integration-mode-priority should the counter time out. The bridge amplifiers are powered and the appropriate temperature can be sampled on the two test points with a d.v.m. (1 volt \equiv 10degC).

Setting up


The design contains a rather confusing array of switch settings for testing and setting up, most of which turned out to be unnecessary. The bridge amplifier gains

and offsets can easily be set up in the hold mode using standard resistors ($100\Omega \equiv 0^\circ\text{C}$ and $110\Omega \equiv 26.0^\circ\text{C}$). The v-to-f offset is set to give a 5Hz tickover at zero ΔT (visible on the l.e.d. in the set-zero switch position). The v-to-f gain is set by adjusting the output to 8.192kHz at a ΔT of 16.9°C. The beat between the v-to-f output and the reference signal from the clock chain should be visible on the l.e.d. with the test switches set to set-gain. Alas, in practice it is far more visible on a 'scope.

One vital ingredient missing from the design is a way of detecting leaky c-mos chips. With complex battery powered equipment, one leaky chip or a floating gate can mean the difference between microamps and milliamps of battery consumption. But which chip is it? Desoldering them at random from a double-sided printed circuit board is a recipe for disaster, and yet a few 100ohm resistors in the power rails to localize the fault could have saved many boards from the bin.

This design dates from 1980. A production run of 100 were made in 1981 and have performed reliably since then. With

the close of the Pennyland field trial they are likely to be passed on to further trials. Although the design is a little dated, it is still difficult to get the same performance at the price from a micro design (the components excluding board and box come to about £120), but it is only a matter of time.

Members of the Open University Electronics Common Facility transformed the scruffy prototype into a production device. Funding for the Pennyland project came from the Department of Energy, through their Passive Solar Energy Programme, and the Department of Environment as an extension of their 'Better Insulated House' programme. 

References

1. Energy Projects in Milton Keynes, S. Fuller, J. Doggart & R. Everett, 1982. Available from Milton Keynes Development Corporation.
2. Simple data-logging instrumentation for monitoring the thermal performance of buildings, Charles Newcomb, Proc. 5th Passive Solar Conference, University of Massachusetts, 1980.

APPENDIX 6

COMPUTER DATABASE SUMMARY

APPENDIX 6: Summary of the Pennyland computer database

Access to the Pennyland database is provided in the first instance by three main programs, look, kool and select, and of these look and select have been fundamental to the analysis of the Pennyland data. The purpose of this appendix is to provide a introduction to the tasks that these programs perform, without going into the details of the computing. This will, we hope, enable the general reader to appreciate the manipulations that were done and could be done on the data.

Look

The Pennyland data is stored in the computer in a specially compacted form, which is not readable except with difficulty by people. There are two reasons for storing the data like this - it saves space and it makes access to any given piece of data faster because the computer has fewer numbers to sort through before finding the ones that the user wants.

Primary access to the database is through the look program. The output from look is in the form of cumulative meter readings. Each line of output carries all the data for one house that was recorded on a given day, together with the data and house number. Data for single houses can be output, or for almost any arbitrary subset of houses. Houses can be asked for by number, or by estate, insulation level (at Pennyland), by terracing level, by orientation, by passive solar variant, by monitoring level and by size.

Look can be asked to output data between two given dates, or before or after a given date. If no date is specified, all the data for the given houses is output.

So look can be asked to output data for all the intensively monitored, south west facing, end of terrace, dual aspect Pennyland 1 houses; or for the data for houses 1 and 2 in March 1982; and so on.

To sum up look's purpose is to allow the user to choose data for whatever houses and dates they want, but it doesn't do anything with the data except output it in a readable format.

Select

There are two things wrong with the raw output from look - the data is in the form of cumulative meter readings in the units that each given meter works in, and it consists of all the meter readings for each house and date.

To be useful, the data needs to be differenced and averaged, expressed in sensible units (watts or kWh per day, and °C) and data for only one meter at a time needs to be output. For example we may want to output weekly average gas consumptions in watts for a given set of houses. It is the purpose of the select program to do this job. Output from select consists of the data, the house number, an indication of whether we think the house was occupied over the period between the current date and the last one, and the data value.

If select cannot work out a sensible average value for a given house for a given week (say because the meter reading for the current week was missing) then the data value is replaced by a suitable comment

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("missing", "absent", "reset" or "bad").

As well as taking its main input from the look program, select also knows about two other sources of data. These are a file of daily average outside temperatures in °C and a file of daily average insolation on a vertical south facing surface. These were measured as part of the Linford project, but are essential to the analysis of the Pennyland data. Select can output average insolation or temperature corresponding to the dates on which data for any set of houses was measured. It can also use the outside temperatures to work out absolute internal temperatures averaged over each period.

Output from select can be graphed, averaged, or analysed as required, and several additional programs were written to do this.

Kool

Kool, as its name implies, does the reverse of look; it takes look output and stuffs it back into the compacted database. Kool can either completely remake the database from expanded data for all houses and dates, or it can add to it, or change data already in the database. Its one major failing is that it cannot delete a line from the database.

It is very important that the data in the database is not full of errors, and kool allows mistakes to be corrected by replacing duff values with correct ones. In addition kool carries out checks on the supposedly correct data that it has been given to put into the database; if the format is wrong, if the number of data items for the given house is wrong, then kool throws the new data out, and informs the user.

APPENDIX 7

~~PRESSURE TESTS AND INFILTRATION RATES~~

APPENDIX 7: Pressure tests and infiltration rates at Pennyland and Neath Hill

7.1 Summary

Pressurisation tests were done on 7 houses at Pennyland and Neath Hill, which showed that the Pennyland houses are about 3 times tighter than a sample of UK 19 houses measured by Warren of the BRE (Warren 1982), while the Neath Hill houses are about as tight as Warren's sample.

We have used a simple model of air infiltration due to Warren to try to estimate the air infiltration rates in the Pennyland and Neath Hill houses due to the stack effect and wind. For Neath Hill, the infiltration rate over the heating season at a wind speed of 3 m/s, is likely to be in the range 0.3-0.8 ACH; for Pennyland 1, in the range 0.15-0.35 ACH; and for Pennyland 2, in the range 0.10-0.25 ACH. These figures, particularly for Pennyland area 2, appear very low, and different assumptions regarding the pressure exponent of the houses (this term is explained in the next section) would give slightly different results. For example, if we assume a pressure exponent of 0.60 for Pennyland area 2, the heating season average infiltration rate increases slightly to 0.14-0.31 ACH. Lowering the pressure exponent has the biggest effect at low infiltration rates. It would seem likely that if anything the pressure exponent would be higher in the tightly sealed Pennyland houses than at Neath Hill, making the difference in infiltration rates even greater.

The predicted difference in infiltration rates between Neath Hill and Pennyland 1 may be equivalent to some 1100-1600 kWh/a useful space heat (based on an effective difference in air change rates of 0.25-0.35 ACH). A direct measurement of infiltration rates in these houses would enable us to get a better idea of their likely range, and help us answer the other outstanding question in this area, which is, what is the effect of opening the windows in these houses?

7.2 The data

Pressurisation tests were done on 4 of the houses at Pennyland (1 on Pennyland area 2) and 3 houses at Neath Hill, by David Etheridge of BGC (Etheridge 1983). These tests involved pressurising the houses with a fan to a pressure of 50 Pascals (about 5/10000 of an atmosphere) and measuring the air flow necessary to maintain this pressure difference.

Air flow at 50 Pa (m ³ /s)		
house id	vents closed	vents open
35	0.31	0.41
44	0.36	0.46
55	0.32	0.44
61	0.30	n/a

The results for the Neath Hill houses are

Air flow at 50 Pa (m ³ /s)		
house id	vents closed	vents open
3 Saltern Mews	0.73	0.75
51 Glazier Drive	0.85	0.93
34 Currier Drive	0.97	1.09

It is important for us to be able to estimate the infiltration rates that are likely to occur in these houses, under various conditions, given these leakage rates. To do this I have made use of a paper by Peter Warren (Warren 1982), which describes a "physicist's" approach to the problem. This is summarised in the next section.

7.3 A simple theory of infiltration

The rate of air infiltration into a house depends on the distribution of pressures inside and outside the house, and the rate at which air passes through the cracks in the fabric of the house as a function of pressure difference across those cracks. The pressure differences which give rise to air infiltration are due to a combination of stack effect and wind. The "stack effect" is caused by the fact that in the heating season, the air inside the house is warmer than the air outside. The warm inside air tries to rise and forces its way out of the top of the house, while cold outside air forces its way in at the bottom. The house basically tries to behave like a hot air balloon. The effect of wind needs less explanation.

The air flow Q across cracks in a house is some function of pressure difference p . Where flow is laminar, the relationship is roughly linear, and where flow is turbulent, the flow is roughly proportional to the square root of pressure. Open windows tend to the turbulent end of the range, while cracks in walls tend to the laminar end. Houses as a whole tend to have a pressure exponent of flow n in the range

$$0.5 < n < 0.7$$

A great deal of information on pressure exponents of flow for different types of building elements is given in Kusuda (1976). Construction or use of a model which deals explicitly with the individual behaviour of different types of cracks is beyond the scope of this paper.

Infiltration can be considered initially at the two extremes of buoyancy dominated and wind dominated flow.

Buoyancy dominated flow

The pressure difference due to buoyancy is given approximately by:

$$\Delta p = \Delta T \rho g h / T$$

where ΔT is the temperature difference between inside and outside the

house, ρ is the density of air, g is 9.814 m/s^2 , h is the height of the column of warm air, and T is the absolute outside temperature.

If the air flow rate is Q_T at some test pressure Δp_T then the flow rate due to buoyancy effects will be:

$$Q_B = Q_T (\Delta T \rho g h / (T \Delta p_T))^{n_{FB}}$$

In this equation, F_B takes account of the fact that the whole stack pressure difference appears only across elements right at the top or bottom of the building, and that somewhere in the middle there is a neutral plane where there is no pressure difference at all. During a pressure test, the induced Δp_T is so big that it is essentially constant across all elements. As might be expected, F_B is of the order of $1/4$. If we fill in the constants in the above equation we are left with:

$$Q_B = Q_T 0.0214 F_B \Delta T^n$$

which from values of F_B given in Warren (1982) can be written:

$$Q_B = Q_T 0.00428 \Delta T^{0.7}$$

The above equation for the buoyancy region can be checked against the Linford test house data. At the test house, $Q_T = 0.685 \text{ m}^3/\text{s}$ (Etheridge 1982) at 50 Pa, and the volume of the house is 264 m^3 . An exponent of 0.7 gives the following equation for infiltration.

$$Q_B = 0.040 \Delta T^{0.7} (\text{ACH})$$

and fits Etheridge's (op cit 1982) measurements of stack dominated infiltration rather well (see fig. 1).

Wind dominated flow

For wind dominated infiltration, pressure differences are of the order $C_D \rho u^2$ where C_D is surface pressure coefficient (normally less than 1). So

$$Q_W = Q_T (\rho u^2 / \Delta p_T)^{n_{FW}} F_W(\phi)$$

where F_W carries information about the distribution of cracks and pressure coefficients around buildings of different types. ϕ is the direction of the wind (in radians) with respect to the front of the building. $\phi = \pi/2$ is a wind blowing onto an end wall of the house, or along a row of terraced houses, and $\phi = \pi$ is a wind blowing in the back door. For a pressure coefficient of 0.7,

$$Q_W = Q_T 0.0758 u^{1.4} F_W(\phi)$$

For any given house type $F_W(\phi)$ is a more or less complicated function. Warren produces data for a mid terrace house which is a fairly good sinusoid. He presents a table of values of F_W at intervals of $\pi/2$, to which fairly simple functions can be fitted.

The above formula can be compared with an equation that Etheridge fitted to the Linford test house data (op cit 1982, as modified by Everett). I have kept Etheridge's notation in which R_H is used instead of Q_W for infiltration rate.

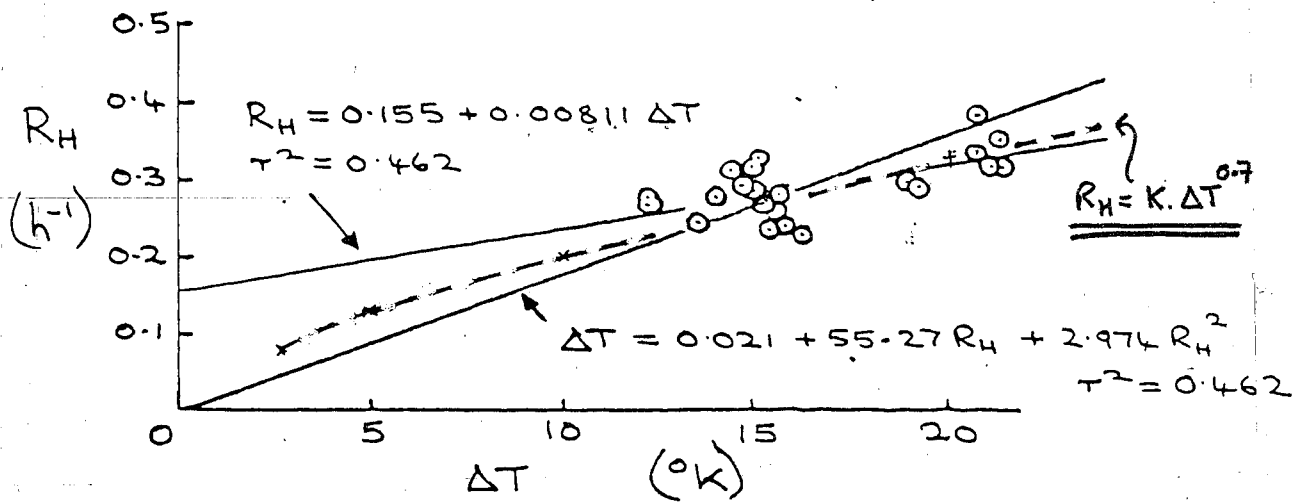


Figure A.7.1 Air infiltration vs. ΔT
for Linford test house (from Etheridge, 1981)

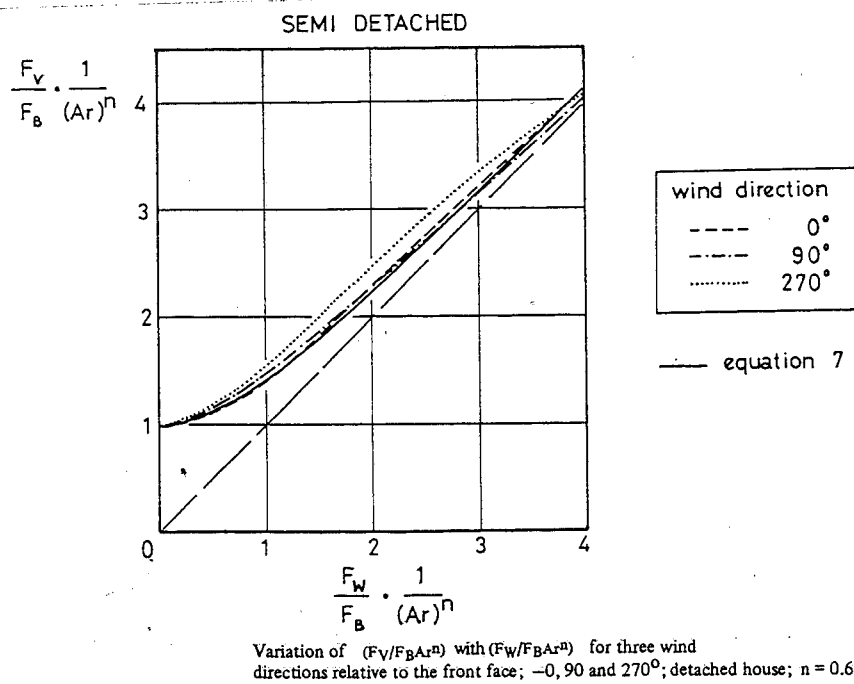


Figure A.7.2

Theoretical air infiltration response for
different wind directions (from Warren, 1982)

A.7.5.

$$R_H = [(0.193 + 0.0128u^2)^{1/2}f(\phi)]$$

where $f(\phi) = 1.16 + 0.478\cos(2\phi)$ if $\pi < \phi < 2\pi$ and $f(\phi) = 1.638$ elsewhere. It is worth noting that the power law relating Q_W to u is considerably simpler than the expression used by Etheridge and is identical to it, to all intents, over the required range of u . The theoretical equation for the Linford test house can be compared to the above empirical fit to the measured data:

Wind on the exposed end wall $\phi = \pi/2$				
wind	air change rate ACH			
m/s	Warren	Etheridge/Everett	ratio	
6	0.783	0.605	1.29	
10	1.60	1.27	1.26	

Wind on the sheltered end wall $\phi = 3\pi/2$				
wind	air change rate ACH			
m/s	Warren	Etheridge/Everett	ratio	
6	0.435	0.252	1.73	
10	0.89	0.528	1.69	

The combined effect of stack effect and wind

Warren's general expression for infiltration Q_V is

$$Q_V = Q_T(\rho u^2 / \Delta p_T)^n F_V(A_R, \phi)$$

where $A_R = (\Delta T g h / (T u^2))$ Fig 2 shows the behaviour of F_V . Warren suggests the following equation for F_V :

$$F_V / (F_{BA_R})^n = (1 + [F_W / (F_{BA_R})^n]^2)^{1/2}$$

The full equation for Q_V then boils down to:

$$Q_V = Q_T(a^2 F_B^2 \Delta T^{2n} + b^2 F_W^2 u^{4n})^{1/2}$$

where $a = (\rho g h / (T \Delta p_T))^n$ and $b = (\rho / \Delta p_T)^n$

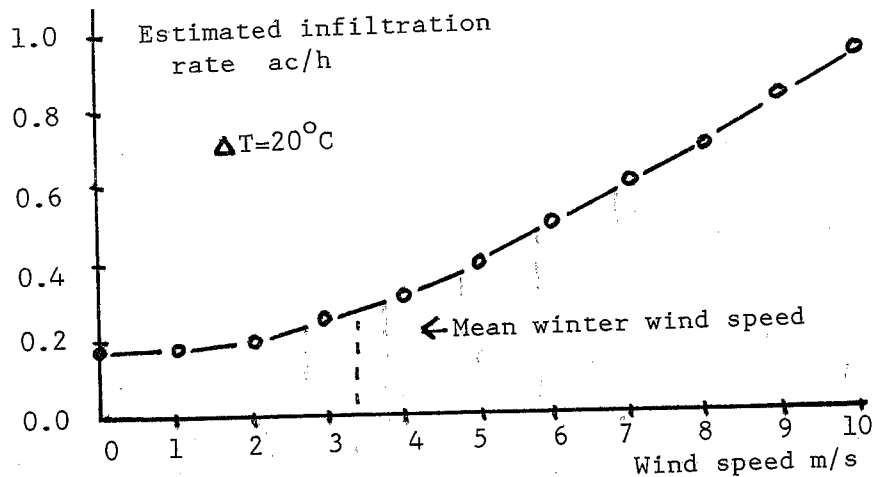
Conclusion

The predictions of infiltration rate at Linford based on the theory set out in Warren (1982) are, I think, reasonably good considering that only the pressure exponent was allowed to vary when fitting the model to

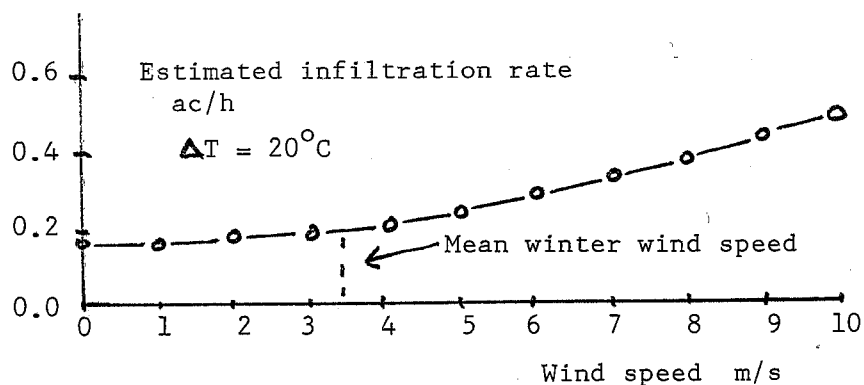
buoyancy dominated measurements. The theory is apparently worst when trying to predict the effect of winds of different directions.

7.4 Prediction of infiltration rates at Pennyland and Neath Hill

To estimate the behaviour of infiltration rates at Pennyland and Neath Hill, I have used the theory set out above, with the pressure exponent of flow equal to 0.7, since this seemed to fit the Linford test house data fairly well. The resulting infiltration rate for the Pennyland 2 house (house 61) are shown below (these are estimated on the assumption that house 61 is mid terrace, for illustration). For winds blowing directly onto the front of the house:

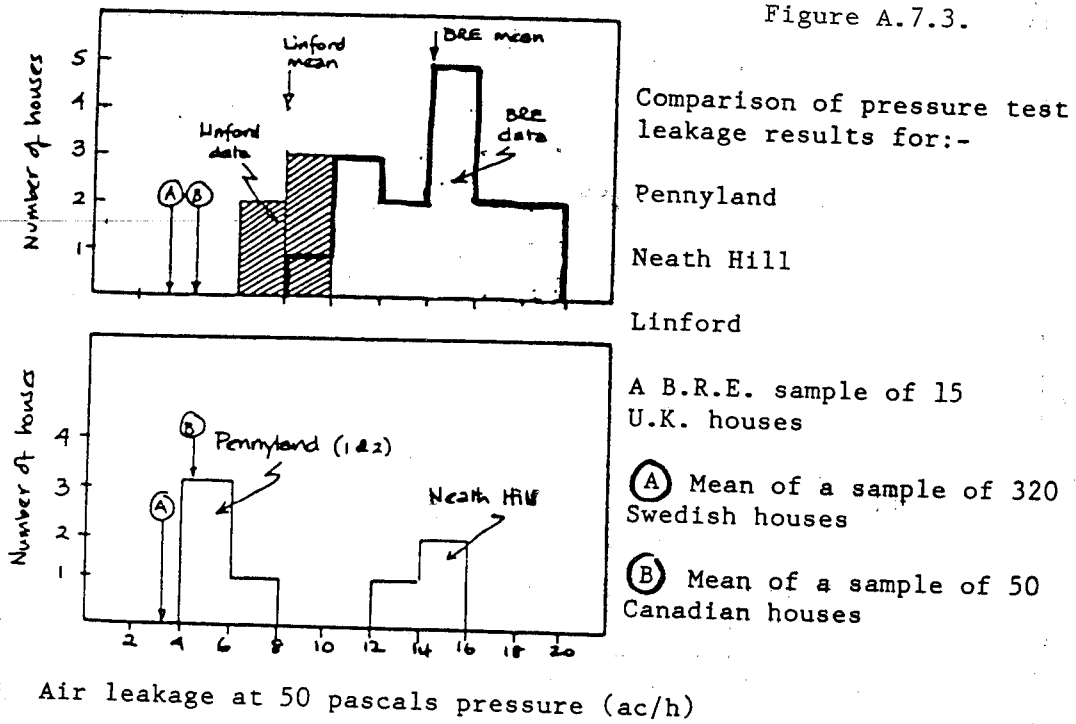


For winds blowing along the length of the terrace:



These figures suggest that the infiltration rate in this house is very low. At a mid winter ΔT of 20 K the wind speed has to be greater than 3 m/s before Q_v exceeds 0.2 ACH. This should not be surprising, given that the value of Q_T for this house is 5 ACH, close to the current Swedish building regulation of 3 ACH, and rather less than the mean for 19 "modern houses" measured by the BRE, of 13.9 ACH (Warren 1982). Figure 3 shows the pressure test results at Pennyland and Neath Hill superimposed on Warren's results.

Figure A.7.3.



7.5 References

Etheridge (1981), "Leakage characteristics of houses at Great Linford". Report WH/T/R&D/81/96, British Gas Corporation, 1981.

Etheridge (1982), "Ventilation measurements in an Open University test house". Report WH/T/R&D/82/207, British Gas Corporation, 1982.

Etheridge (1983) "Neath Hill and Pennyland pressurisation tests", Watson House internal note (private communication), British Gas Corporation, 1983.

Warren (1982), "A simple method of predicting infiltration rates in housing". Energy conservation in the built environment, Dublin 1982.

Kusuda (1976), "NBSLD, the computer program for heating and cooling loads in buildings". US National Bureau of Standards, 1976.

APPENDIX 8

WEATHER IN MILTON KEYNES

APPENDIX 8 : The weather in Milton Keynes: temperature, solar and windSummary

Temperature, solar radiation and wind speed and direction measurements have been made at Great Linford (about 1/2 mile from the Pennyland estate) during the course of the project. These are summarised below. The monthly mean insulations are close (mostly $\pm 5\%$) to the monthly means at the nearest Meteorological Office station at which solar radiation is measured on vertical surfaces (Bracknell). The annual degree days (base 15.5°C) are very close ($\pm 2\%$) to a weighted mean UK degree day figure used by the British Gas Corporation. The 10 m wind speed averaged over the 1982/3 heating season (October 1982 to April 1983) is 3.4 m/s. This is rather less than would be expected on an open site in Milton Keynes, but it should be remembered that these wind measurements were made within about 10 m of a house with a roof height of 8 m. The prevailing wind direction measured at Great Linford is south-west, but this is probably exaggerated by the fact that the anemometer is sheltered to the north by the Linford test house.

In terms of solar radiation and outside air temperature, the weather in Milton Keynes seems to be what one would expect for a site in the English south midlands. Wind measurements at Linford are probably representative of conditions for most of the houses at Pennyland and Neath Hill. The wind speed averaged over the heating season indicates a fairly sheltered environment.

Degree days and mean temperatures at Linford

Ambient temperature was measured at Great Linford over the period 5th November 1981 to 20th June 1983, at intervals ranging between 1 and 15 minutes. The measurements were made with a grade II PRT as used in the DTI's. The sensor was positioned in a Stevenson screen in the back garden of the Linford test house.

From the original data a daily average temperature dataset was constructed. This dataset is about 95% complete. In the tables presented below we have replaced missing daily averages by the mean temperature for the month in which the missing value occurs. Monthly mean temperatures and degree days to a base of 15.5°C were calculated from the "repaired" daily average dataset.

Assuming that the Linford anemometer had an effective height of 2 m and that the velocity-height exponent in the area is about 0.2, the open site mean wind speed over the same period may be about 5 m/s.

A.8.2.

yr	mth	Tav	degree days
81	11	6.69	264
81	12	-0.06	482
82	1	2.78	394
82	2	4.79	300
82	3	6.09	292
82	4	8.96	196
82	5	12.57	95
82	6	16.10	21
82	7	16.87	5
82	8	16.61	18
82	9	14.79	40
82	10	10.26	162
82	11	7.89	228
82	12	4.20	350
83	1	6.93	266
83	2	1.62	389
83	3	6.42	282
83	4	7.20	249
83	5	10.52	154
83	6	14.68	24

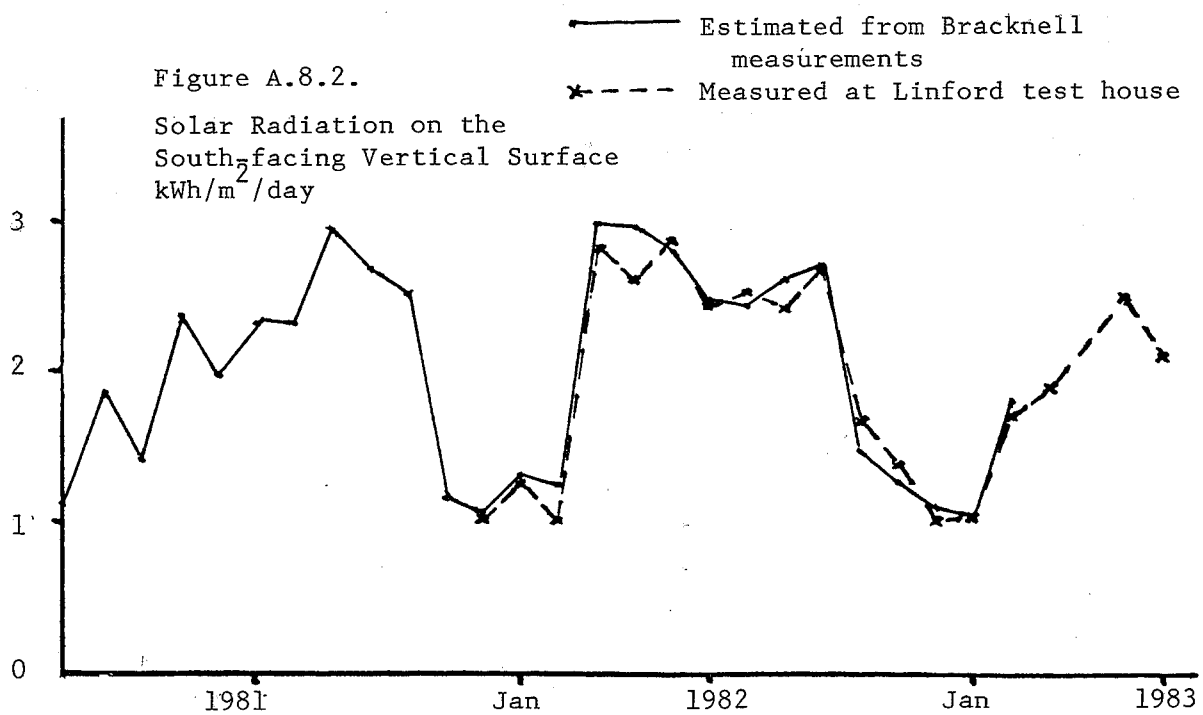
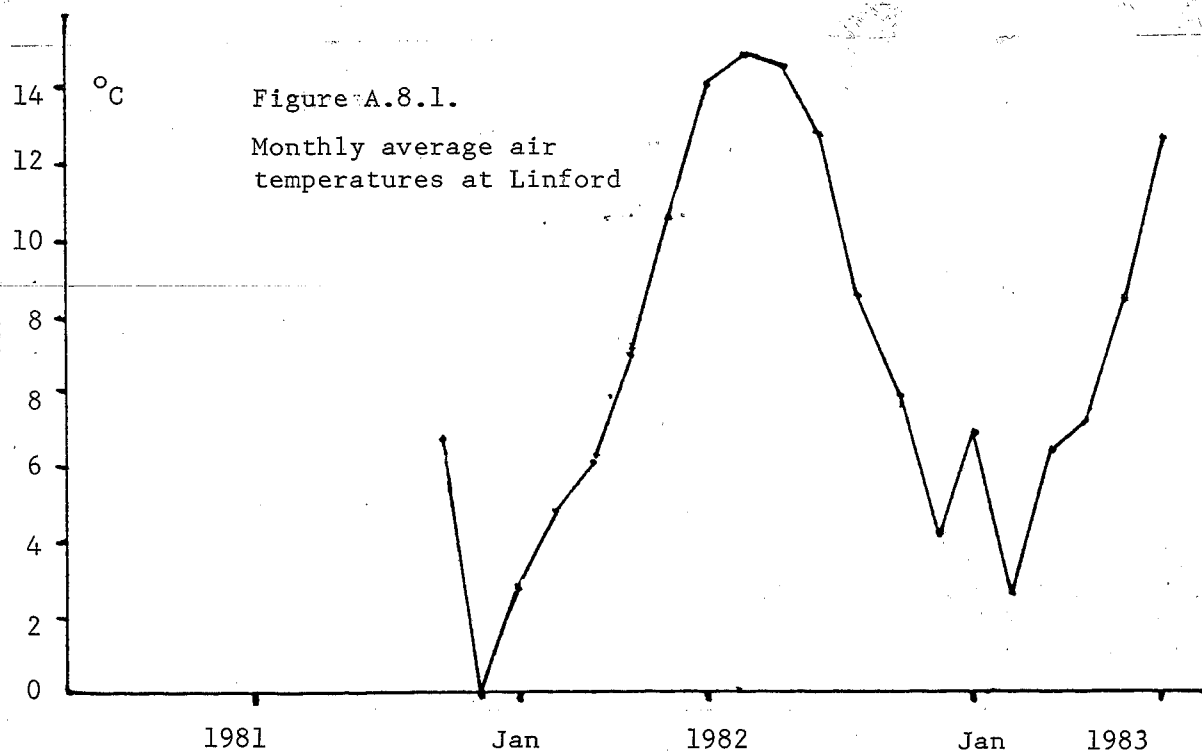
The total degree days over the period November 1981 to October 1982 was 2269. The figure for July 1982 to June 1983 was 2167. This may be compared with a long term weighted average degree day figure for the UK, of 2222 (McNair, 1979). The mean temperature over the heating season (November 1981 - April 1982, plus October 1982) is 5.6°C. The mean summer temperature (May 1982 - September 1982) is 15.4°C. Fig 1 shows the variation of monthly ambient air temperatures at Linford.

It should be noted that although the winter of 1981/2 was overall fairly normal, December 1981 was extremely cold, containing some of the worst weather this century. A minimum temperature of -17°C was recorded at Linford.

Solar radiation at Linford

Solar radiation on a south facing vertical surface was measured at Linford from the 8th of December 1981 to the 20th June 1983. Solar measurements were made with Kipp en Zonen solarimeters. These were mounted at the top of a 10.5 m mast in the garden of the Great Linford test house (see Everett *et al* 1984). The measurements used for the Pennyland project were made with a solarimeter in a vertical south facing plane.

The raw solar data was first converted to hourly and then to daily average files. Gaps in these daily files have been filled in with values measured at Bracknell. To allow for the fact that Bracknell measure vertical solar radiation with no ground reflection we have added 10% of the measured radiation on a horizontal surface to the figures for radiation on a vertical surface. This is a small correction in all months, particularly in winter. The mean radiation intensities in each month are shown below:



A.8.4.

date 1981	average solar at Linford	kWh/d (watts/m ²) at Bracknell
Jan	-	1.13 (69.6)
Feb	-	1.87 (77.9)
Mar	-	1.41 (58.8)
Apr	-	2.38 (99.2)
May	-	1.99 (82.9)
Jun	-	2.33 (97.1)
Jul	-	2.34 (97.5)
Aug	-	2.95 (122.9)
Sept	-	2.69 (112.1)
Oct	-	2.02 (84.2)
Nov	-	1.17 (48.8)
Dec	1.06 (44.2)	1.09 (45.4)

date 1982	average solar at Linford	kWh/d (watts/m ²) at Bracknell
Jan	1.24 (51.7)	1.33 (55.4)
Feb	1.00 (41.7)	1.27 (52.9)
Mar	2.81 (177.1)	3.01 (125.4)
Apr	2.60 (108.3)	2.99 (124.6)
May	2.84 (118.3)	2.81 (117.1)
Jun	2.42 (100.8)	2.51 (104.6)
Jul	2.52 (105.0)	2.48 (103.3)
Aug	2.40 (100.0)	2.64 (110.0)
Sept	2.66 (110.8)	2.73 (113.8)
Oct	1.68 (70.0)	1.51 (62.9)
Nov	1.38 (57.5)	1.31 (54.6)
Dec	1.00 (41.7)	1.12 (46.7)

date 1981	average solar at Linford	kWh/d (watts/m ²) at Bracknell
Jan	1.02 (42.5)	1.08 (45.0)
Feb	1.71 (71.3)	1.84 (76.7)
Mar	1.90 (79.2)	-
Apr	2.50 (104.2)	-
May	2.09 (87.1)	-
Jun	2.88 (120.0)	-

From the above tables we can see that the monthly mean insolation at Great Linford is normally within about $\pm 5\%$ of the equivalent value for Bracknell estimated from measurements made by the Meteorological Office. Fig 2 shows the pattern of monthly solar radiation at Linford and Bracknell.

Wind at Great Linford

Wind speed and direction were measured with a rotating cup anemometer and a windvane, both supplied by the Reading University Department of Meteorology, which were mounted at the top of the Linford test house weather mast. Reliable wind measurements did not begin until October 1982, and continued until the beginning of June 1983.

The frequency distribution of wind speed, and wind roses are presented in figs 3, 4 and 5. A time series plot of the daily average wind speed is shown in fig 6.

Correlation of temperature and solar radiation

The degree to which solar radiation and air temperature are correlated is an important consideration in any attempts to estimate the solar aperture of a house by regression techniques. The weekly weather data has been analysed to this end and it has been found that solar radiation is not seriously correlated with air temperature over the heating season. Details of this analysis and the consequences for attempts at 'house characterisation' will be found in the companion Linford Rapid Thermal House Calibration report.

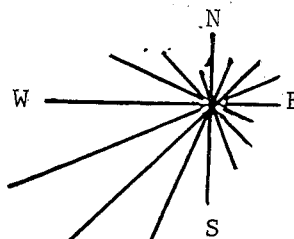
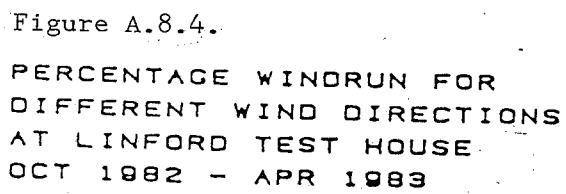
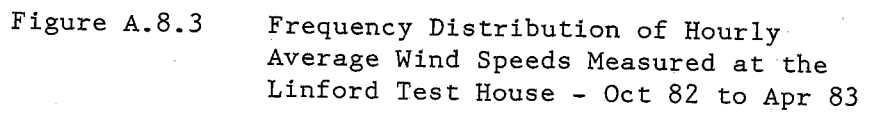
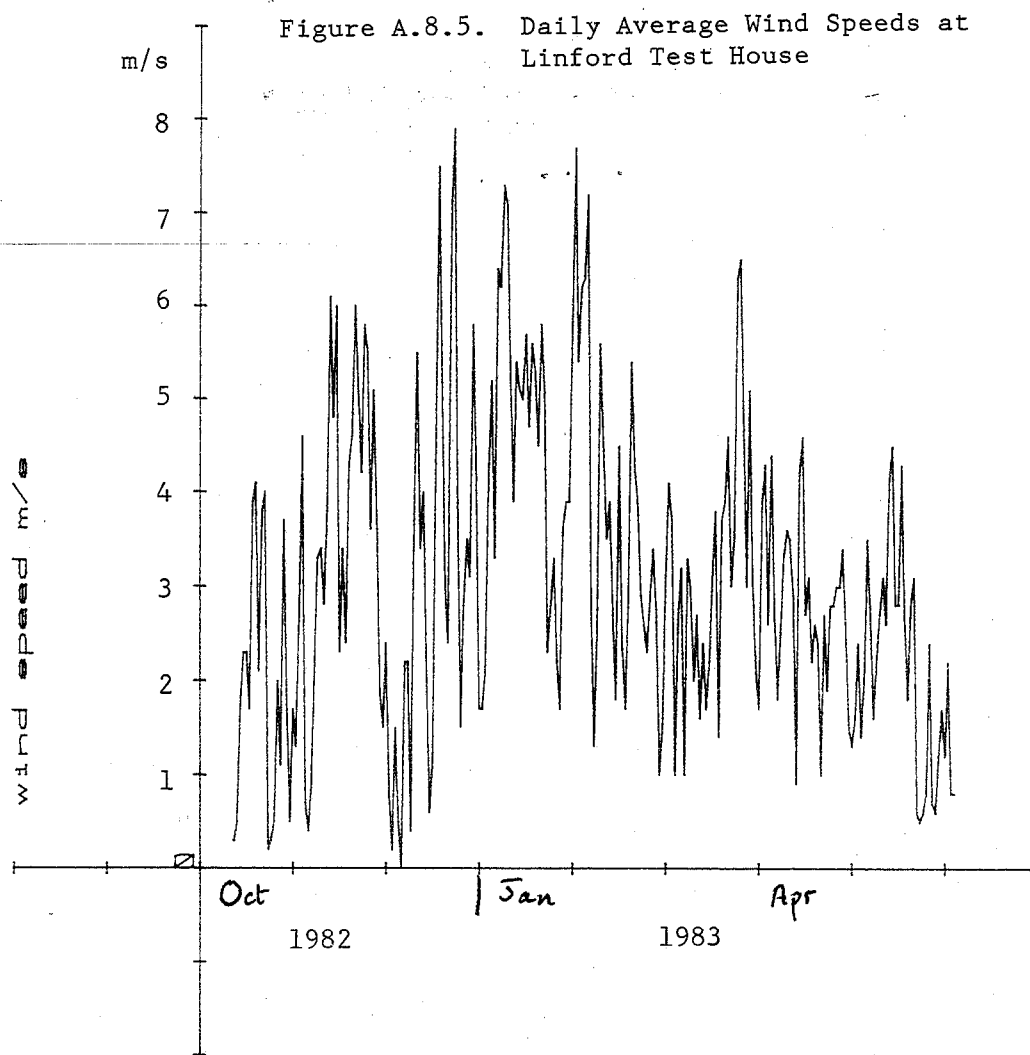


Fig. A.8.4
Wind
Rose

A.8.7.



APPENDIX 9

DATA CLEANING, QUALITY AND AVAILABILITY

APPENDIX 9: Data cleaning, quality and availability1. Why the data had to be cleaned

The various meters at Pennyland and Neath Hill were read and the readings written down in books (either weekly or monthly) and transferred manually to the computer database in batches of about one week. This was all done by one person, a technician. The reading of the meters appears to have been almost error free (except for certain systematic errors which will be described later), with something like 10% of the values initially in the database being wrong. It is worth describing the more easily identifiable types of errors before going any further. Remember that the data is stored as cumulative totals of energy or degree days, and that the consumption of energy or the mean temperature in any week is the difference between this week's reading and last week's (backward difference).

1. Single digit errors. Single digit errors occurring in the most significant digit of a week's reading result in dramatic fluctuations in the differenced data. These fluctuations come in pairs, one negative and one positive, and are very easy to see in plots or listings of the differenced data. Errors in less significant digits are more difficult to spot, but may be important at later stages of analysis. Errors in the least significant digit are normally undetectable except by careful comparison of the computer database with the data books, and can be safely ignored.
2. Repeated weeks. A frequently occurring error was where the data for a given week had been entered twice. This often reveals itself in plots or listings of the differenced data as a value of zero followed or preceded by a value which is about twice as big as it ought to be. This type of error was probably caused by reading the wrong line of data from the data book during data entry.
3. Data 'borrowed' from a different house. This error causes similar behaviour to single digit errors, i.e. pairs of low and high values in the differenced data.
4. Meters mixed up. This error was particularly common in the Neath Hill gas meter data, where boiler gas and total gas meter data would repeatedly change places as the weeks went by, and was the only one which occurred as frequently in the data books as in the computer database. This sort of error was sometimes extremely difficult to sort out in those houses with no gas cooker, because the two meters were measuring the same gas flow. Indeed this similarity of behaviour was almost certainly why the mistakes happened in the first place. This is perhaps a lesson for future field trials.
5. Data quality flags wrongly set. The most obvious such error was where a meter had been reset and this had not been marked in the database. In such cases the result would normally be a single large negative value in the differenced data.

Examples of plots of cleaned and uncleaned data are shown in figures A.9.1 and 9.2 to illustrate some of the types of error mentioned above. The errors described above are reasonably straight-forward. The whole thing became rather more difficult where there was more than one type of error in the same few weeks of data.

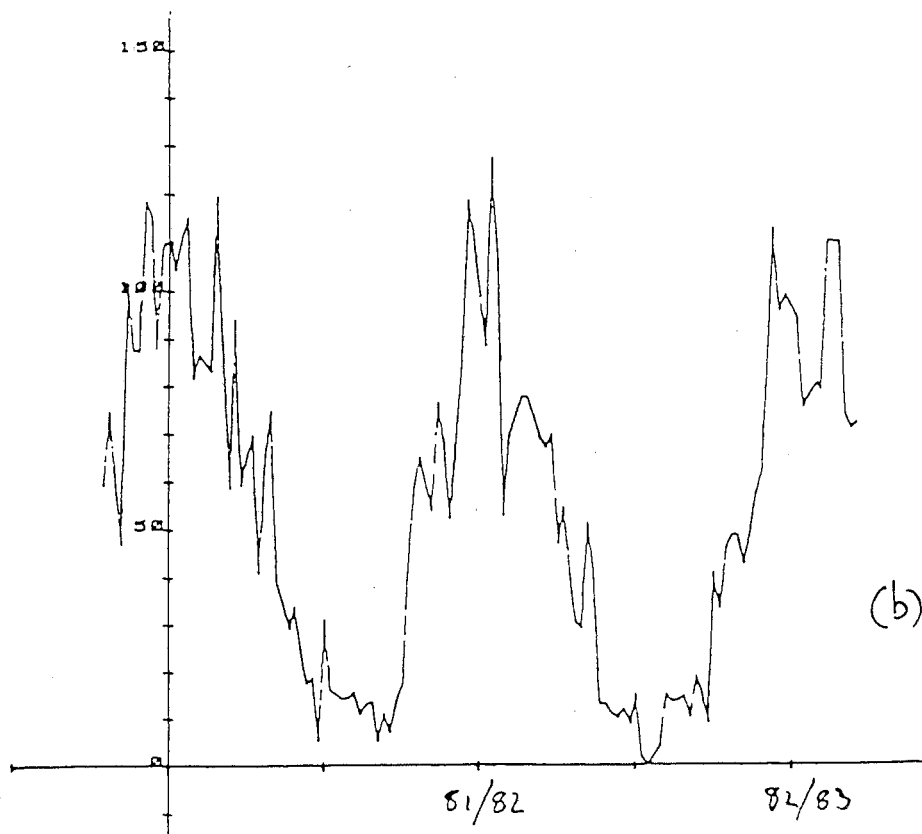
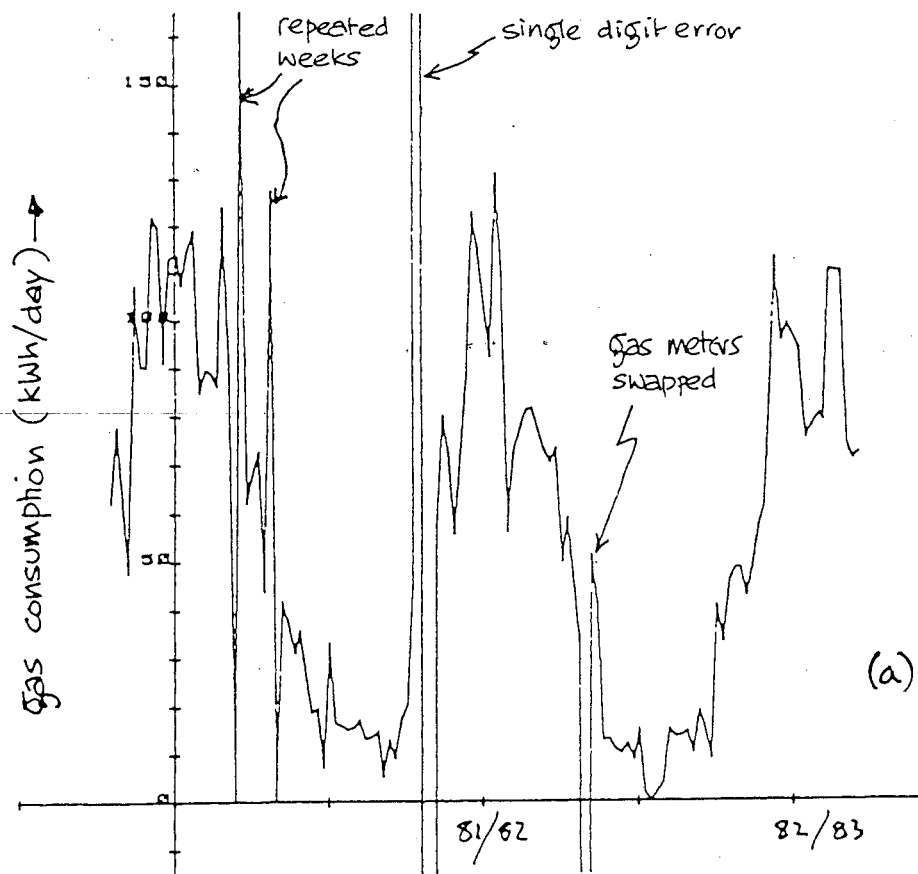


Figure A.9.1. Gas meter data (a) in raw form
(b) after cleaning

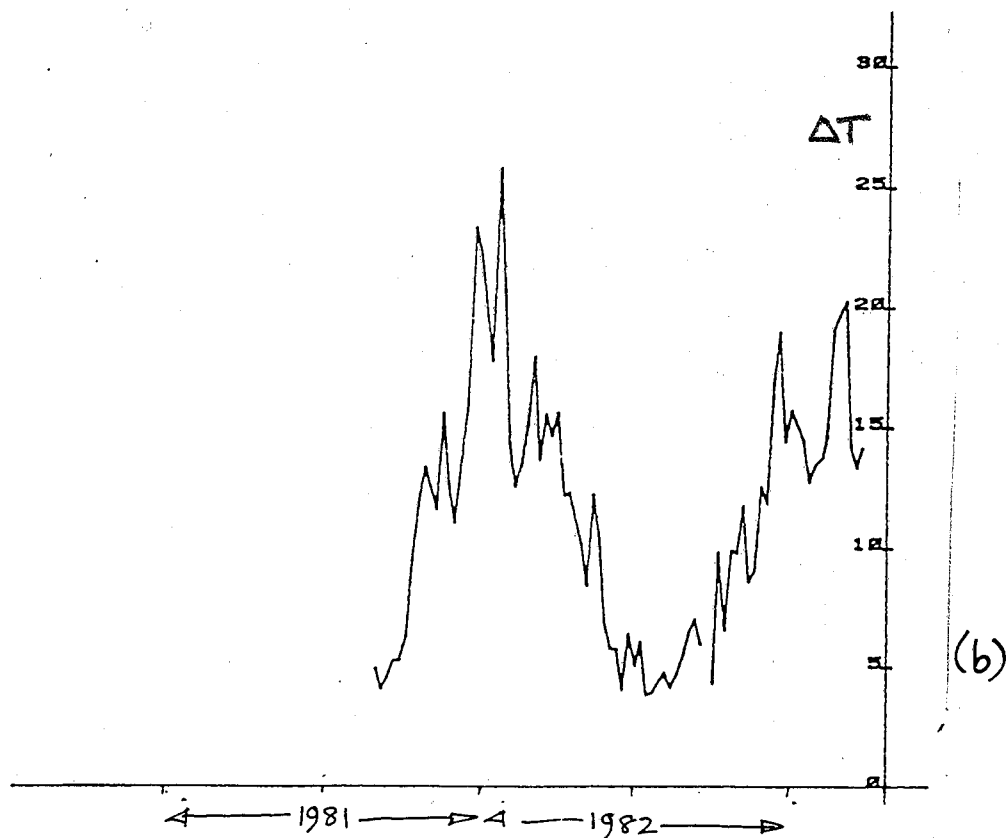
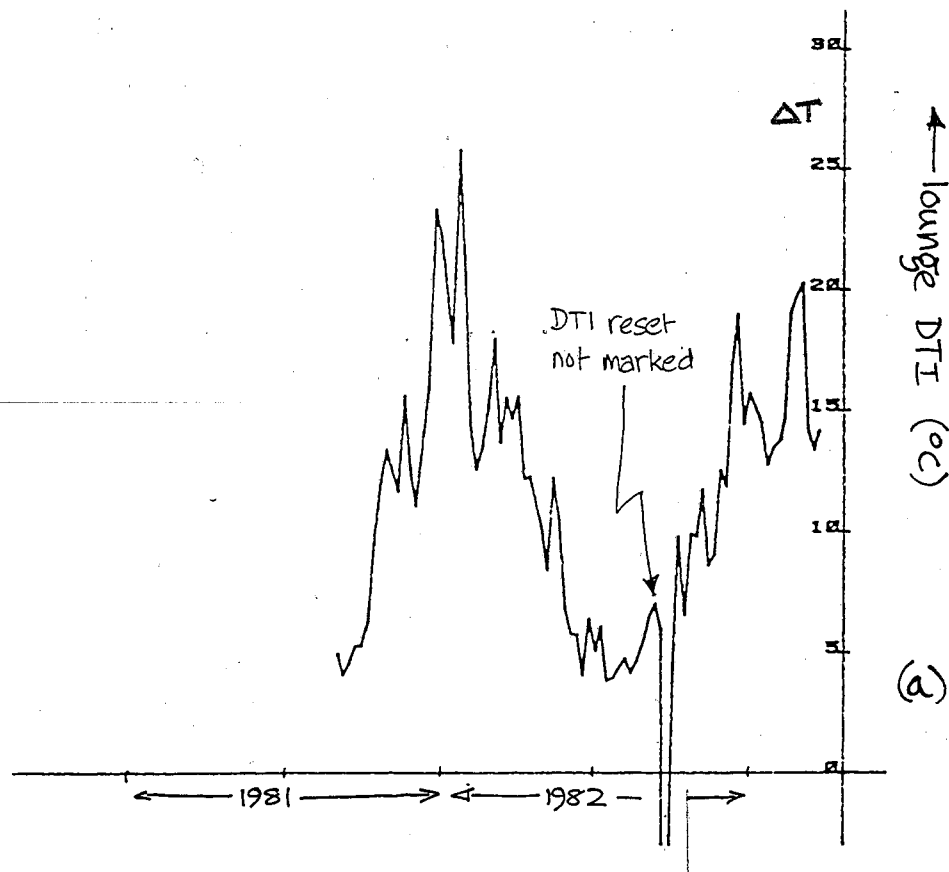


Figure A.9.2. DTI data a) before cleaning
b) after cleaning

2. How the data was cleaned

It is important to remember that the database handling programs that were used to look at and alter the database were not finalised until the spring of 1983. Some cleaning of the database was done in 1982, but the programs that were then being used were clumsy, difficult to use and slow, and little time was therefore spent on this work. When the final version of the look program became available (in March 1983) the cleaning got under way. The method which was finally used was as follows:

1. The output from the 'look' program for each house was placed in a file (an example is shown below) and the contents of this file were then compared entry by entry with the data book.

date	house	total	el	boiler	DTI	space		
	no.	gas		gas	lounge	kitchen	bedroom	heat
80 10 8	1g	278.7g	1502.70g	257.1g	0.0a	0.0a	0.0a	0.0a
80 10 15	1g	293.1g	1560.35g	270.8g	0.0a	0.0a	0.0a	0.0a
80 10 22	1g	311.1g	1638.02g	288.1g	0.0a	0.0a	0.0a	0.0a
80 10 29	1g	325.6g	1726.38g	301.9g	0.0a	0.0a	0.0a	0.0a
80 11 5	1g	336.6g	1776.74g	312.7g	0.0a	0.0a	0.0a	0.0a
80 11 12	1g	361.4g	1853.73g	336.2g	0.0a	0.0a	0.0a	0.0a
80 11 19	1g	382.2g	1925.10g	356.4g	0.0a	0.0a	0.0a	0.0a

This comparison was done using a screen editor, and any obvious errors which were found were put right on the spot. Obviously this was a time consuming process (1 to 2 hours per house with practice) but the majority of the errors in the database were spotted this way, in one pass through the data. Data which had not yet been transferred to the computer from the data books was typed in at this stage.

2. The weekly differences for each variable for the house being cleaned were then calculated,* and listed or plotted, and any residual errors were put right. For the houses with a cooker gas meter the difference between the two gas meters (which is boiler gas consumption) was also listed and plotted, and this enabled some quite small errors in the gas meter readings to be spotted. At this stage the data appearing in the data books was assumed to be right, unless there was an obvious error in the book - meters running backward for example.

Note that all but the first 3 columns of the above are followed by a letter. These are the data quality flags which indicate whether the reading is good, bad or missing, whether the meter itself is present or absent, and whether the meter has been reset by the technician.

* Differences were calculated using the "select" program, which is described in an appendix.

3. During the first two stages of cleaning, the data quality flags were set to appropriate looking values. The log books contained frequent annotations made by the technician which helped with this process. Gas and electricity meters rarely went wrong (one did, but for diplomatic reasons we did not do anything about it), and the readings for these meters are therefore nearly always "good", with occasional "missing"s where a meter could not be read or a reading in the data book could not be made to make sense.

At this stage of the cleaning the house flags (the ones that appear immediately after the house number) were also set. The values which were used were "good", "holiday" and "vacant". Holidays and vacancies were judged mainly on the basis of what the electricity and gas meters were doing. Where the house was vacant for a long period of time (for instance when someone had moved out) this was often noted in the data book, but in any case was obvious because of zero or very low and constant gas and electricity consumptions. Holidays are sometimes rather more difficult to spot, since fridges and sometimes the boiler pilot light get left on when people are only away for a week or two. Also unless a holiday coincides exactly with meter reading dates, changes in consumption will not be abrupt, and it becomes a matter of judgement as to when or if a holiday started and finished.

4. When a cleaned and complete file of data for each house was ready, the data could be put back into the compacted database using the kool program. In fact this had to wait until kool had been finished and was not done until over 6 months after the cleaning had been completed. This step provided a last check on the data, as kool does a certain amount of semantic checking as it compacts.

Cleaning the data took some 4 months altogether. Initially the work was done by the research fellow, but when the size of the task became apparent an additional pair of hands (Harry Travis) was hired for a period of two months to help with the work. The total amount of effort devoted amounted to above 15 person-weeks.

3. Data quality and availability

The last date on which data was recorded for the Pennyland and Neath Hill intensively monitored houses was 15th March 1983. The earliest date for which we have data depends on which group of houses we are looking at, and on the variable of interest. The reasons for this ragged start to monitoring are, first that the houses in the different groups (Neath Hill, Pennyland 1 and Pennyland 2) were finished and occupied over a period of about one year, and second that the production and installation of the DTI's was not completed until August or September 1981, nearly a year after the first meter readings were made.

A.9.6.

Information on recording periods is summarised in the table below:

Neath Hill

	81	82
	o n d j f m a m j j a s o n d j f m a m j j a s o n d j f m	
g1	-----	
e1	-----	
g2	-----	
dti		-----
h1		-----
h2		-----

Pennyland area 1, intensively monitored

```

                                81                                82
o n d j f m a m j j a s o n d j f m a m j j a s o n d j f m
g1  -----
e1  -----
g2  -----
dti -----
h1  -----

```

Pennyland area 2, intensively monitored.

	81	82
	o n d j f m a m j j a s o n d j f m a m j j a s o n d j f m	
g1	-----	-----
e1	-----	-----
g2	-----	-----
dti	-----	-----
h1	-----	-----
h2	-----	-----

Pennyland area 1, monthly monitored

	81												82																	
	o	n	d	j	f	m	a	m	j	j	a	s	o	n	d	j	f	m	a	m	j	j	a	s	o	n	d	j	f	m
g1	-----																													
e1	-----																													

Pennyland area 2, monthly monitored

81 82
o n d j f m a m j j a s o n d j f m a m j j a s o n d j f m
g1 _____
e1 _____

The exact position is actually slightly more complicated than the above tables make clear. For example, though the majority of the DTI's did not arrive until July and August 1981, a prototype was installed in house 68 in February 1981. At Pennyland area 1, six heat meters were installed in early March 1981 (houses 21, 22, 23, 24, 25 and 26), though the rest of the heat meters were not recording until June 1981. Some of the monthly monitored houses at Pennyland 2 (houses 77 to 97, and 172 to 192, which all lie to the south of Leopard Drive) were not occupied until late May 1981.

To complete this introduction to the data we show below the periods for which solar and ambient temperature data was measured in Milton Keynes.

Weather data measured in Milton Keynes

	o	n	d	j	f	m	a	m	j	j	a	s	o	n	d	j	f	m	a	m	j	j	a	s	o	n	d	j	f	m	a	m	j		
sol						++++++							+++																						
temp																																			

NB "+" indicates measurements made at New Bradwell (see Ford 1983).

Data can be divided crudely into "good" or "bad". Exactly what these terms mean in the case of the Pennyland and Neath Hill data is explained in more detail in the section on data cleaning, but for the purpose of this exercise, bad data is any data which is marked as missing, bad or reset in the database, whether because of misreadings, meter failure or maintenance, or whatever else. Since we are interested in the performance of the monitoring system, periods when the meters were physically absent form a third category which is not included in the calculation of the ratio of good to all data. The fractions of good data for each variable averaged over the houses in each of the three main groups of intensively monitored houses are shown in figures A.9.3 to 9.5, as functions of time.

The main features of these plots are:

The gas and electricity meters performed very reliably, with an average of about 99% good data. In the case of Pennyland 2, one of the gas meters did not work at all. This was the only one in the project which failed. For these meters, bad data is caused either by misreadings or because the meter reader could not get access to the meter cupboard on the day in question.

The DTI's have about 10% bad data. The averages over the houses in each of the three main groups show rather erratic behaviour in September and October 1982. This was when the DTI's were systematically serviced. When this was done the readings in each DTI channel were unavoidably set to zero. In some of the Neath Hill houses the leads to the DTI were not reconnected correctly after the service, which caused more than one week's bad data.

The heat meters fluctuate between about 40% and 80% good data. An improvement is noticeable around September 1982, which was caused by a concerted effort on the part of the technicians to get the meters working properly. Particularly important is the fact that the fraction of good data for space heat meters on Neath Hill went up from about 30% to about 90%. This makes estimation of the performance of the boilers at Neath Hill rather easier than it would have been.

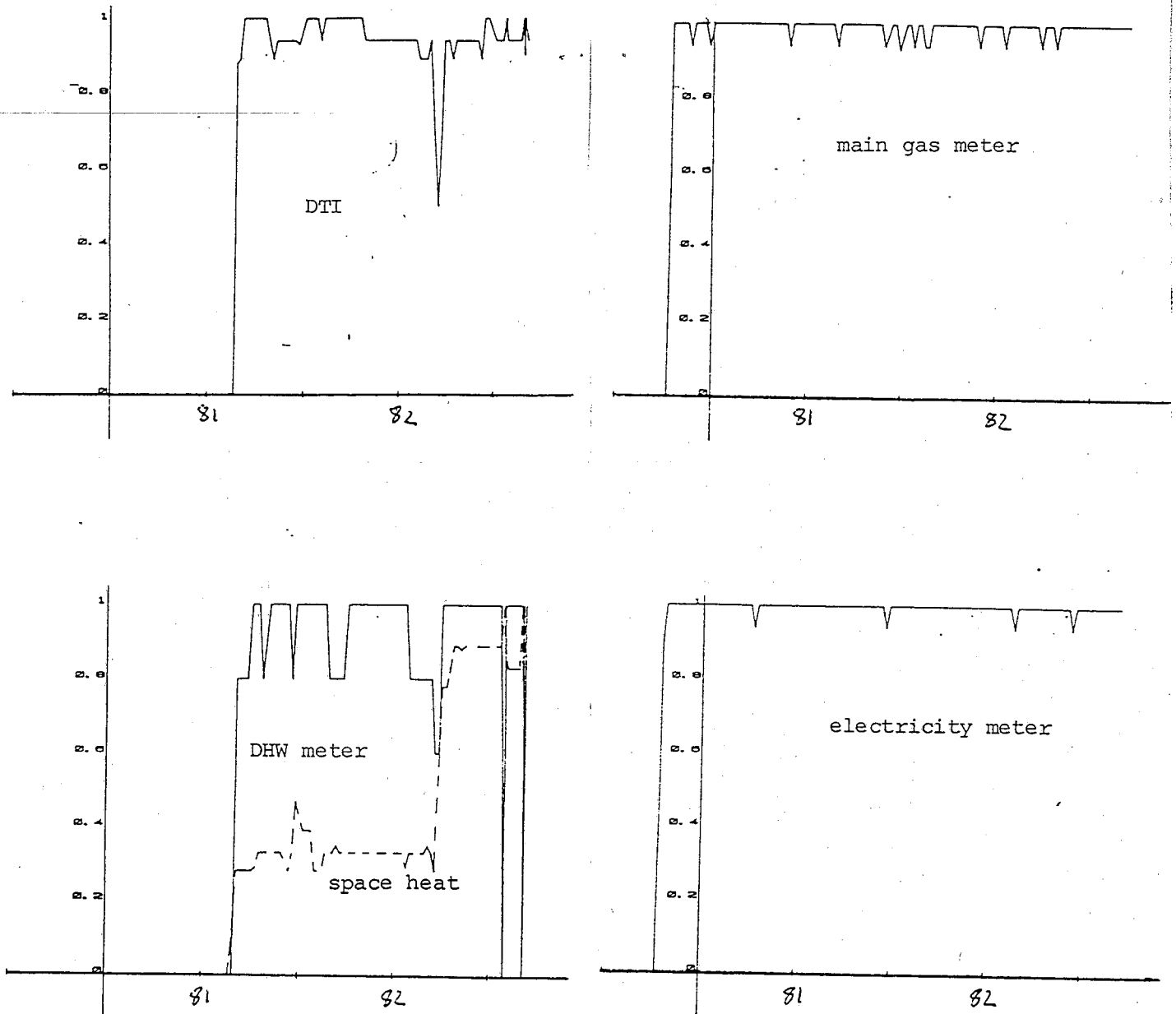


Figure A.9.3. The fraction of monitoring equipment available in the Neath Hill insulated group.

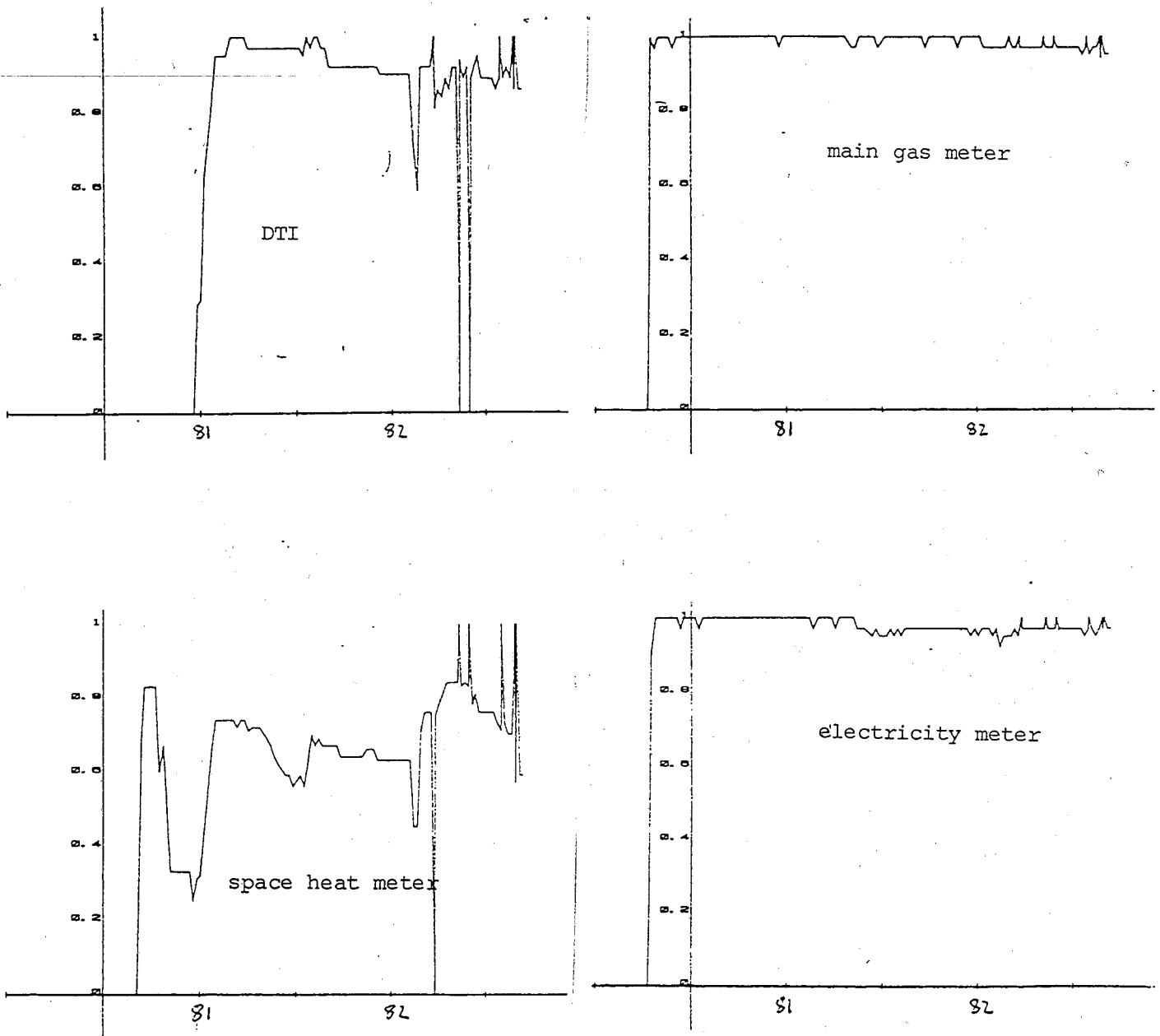
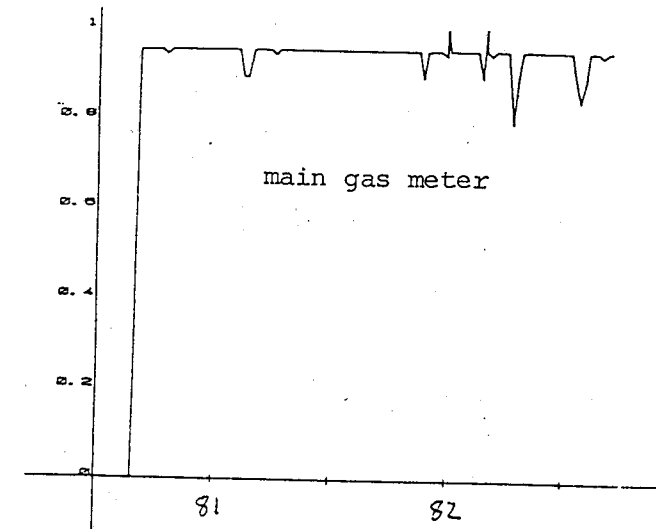
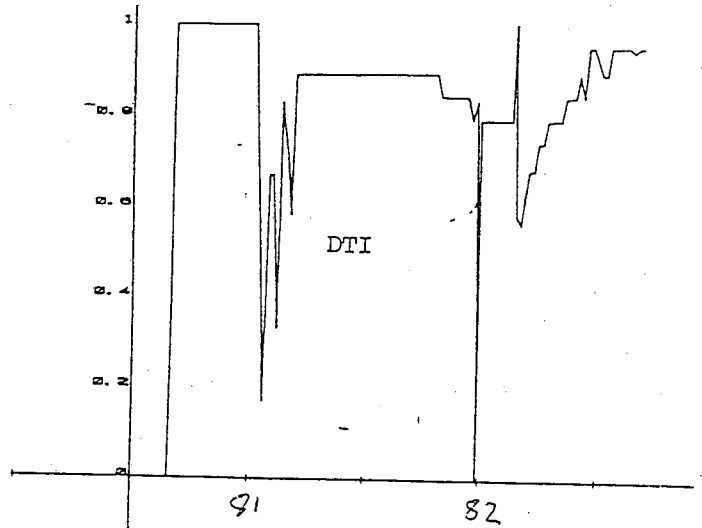


FIGURE A.9.4. Availability of monitoring equipment at Pennyland area 1



D2x



P2x

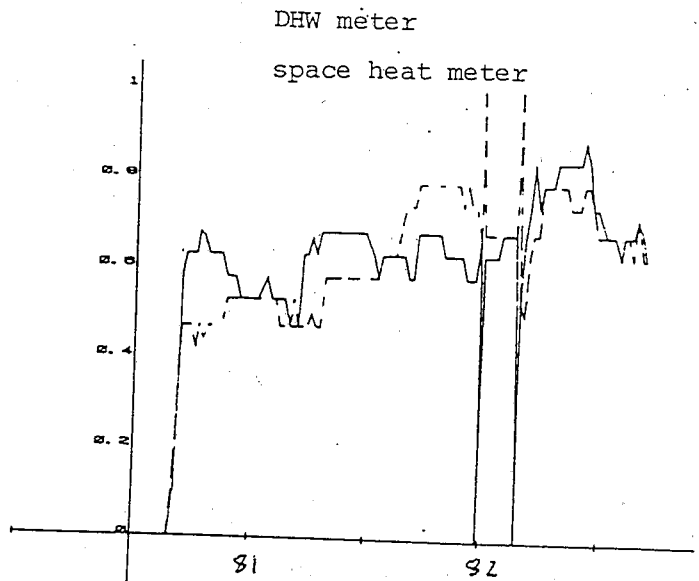
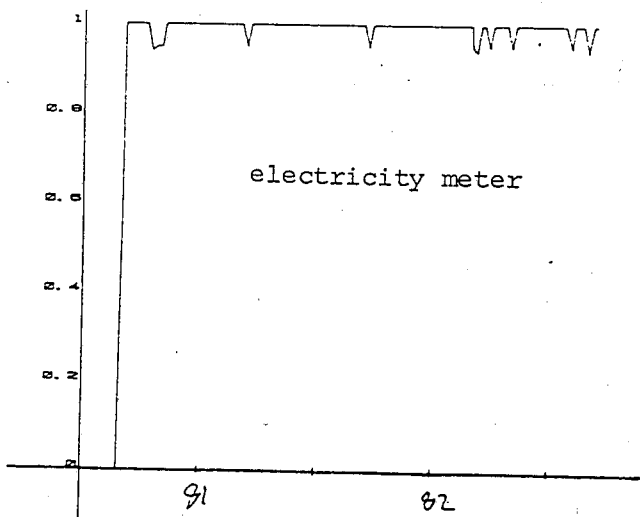
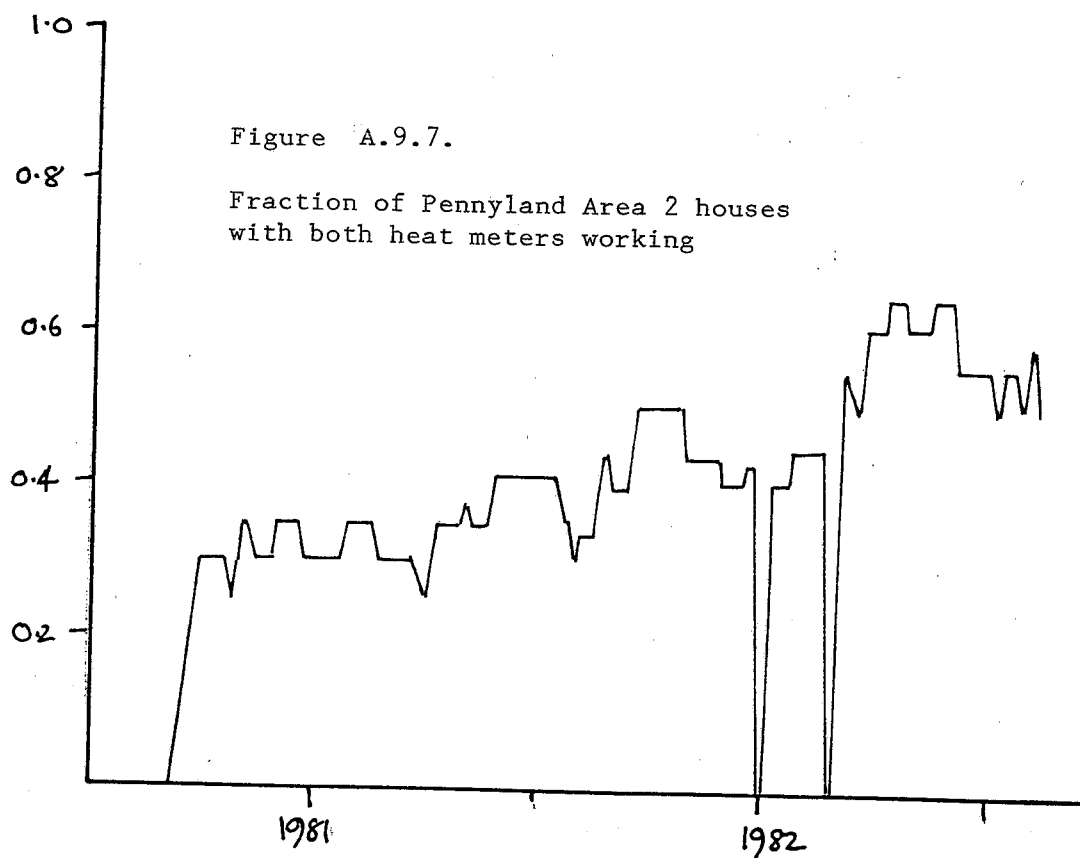
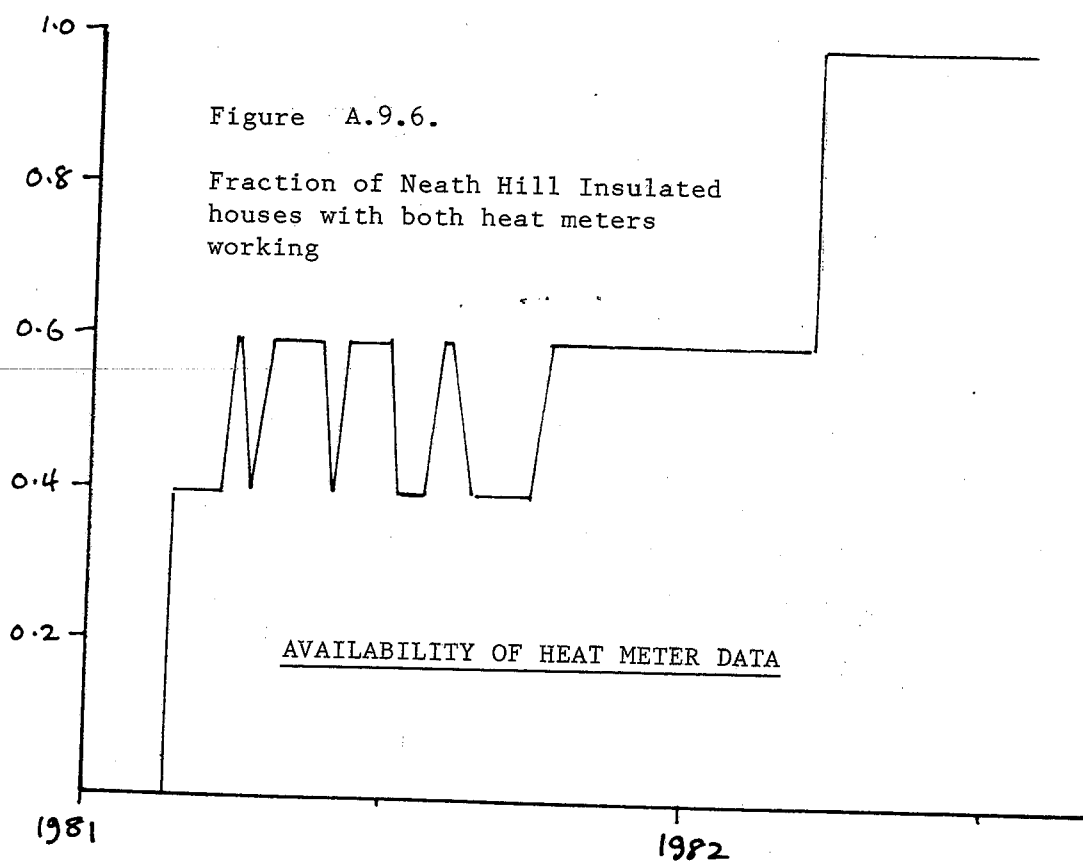


Figure A.9.5. Availability of monitoring equipment at Pennyland area 2

The summaries of data quality which have been presented are not the end of the story. For example given the rather high missing data rates for the heat meters, and the requirement to have both of the heat meters in one house working if an estimate of the boiler efficiency is to be made, it would be useful to know how many houses had both heat meters working over any given period. Obviously, this only applies to Pennyland 2 and 5 of the Neath Hill houses. Figures 9.6 and 9.7 show the fractions of these houses which have good data for both heat meters, as a function of time. These figures emphasise the potential cost in a housing field trial of sort, of equipment failures. At Pennyland 2 it is quite rare to have both heat meters working in more than one half of the houses. These figures also illustrate what is possible with concerted effort - the effect of the work done in September 1982 is to increase the number of houses with good data for both heat meters from about 10 to above 16, out of a total of 26.



APPENDIX 10

BOILER CHARACTERISTICS

APPENDIX 10: Boiler characteristics for Neath Hill and Pennyland houses10.1 Analysis method

The following is a more detailed analysis of boiler efficiency characteristics for houses 4, 10, 11, 15 and 16 at Neath Hill, and all the intensively monitored houses at Pennyland 2 except houses 60, 62 and 66. To try to make more sense of the very scattered data on boiler efficiencies, weekly gas consumption was plotted against weekly boiler output for each of the above houses. Straight lines were fitted to these plots, and the parameters of the line for each house are listed at the end of this appendix. Examples of the plots are shown in figures 1 and 2. These regressions were designed to give an idea of any systematic differences between Neath Hill houses with their high thermal capacity boilers, and Pennyland houses with their low thermal capacity boilers. The intercept of the plot for a given house, determines how quickly the boiler efficiency falls off at part load, while the slope of the plot is the inverse of the asymptotic efficiency.

The mean intercepts and slopes for the two sets of houses are shown below:

Mean boiler characteristics (before correction)

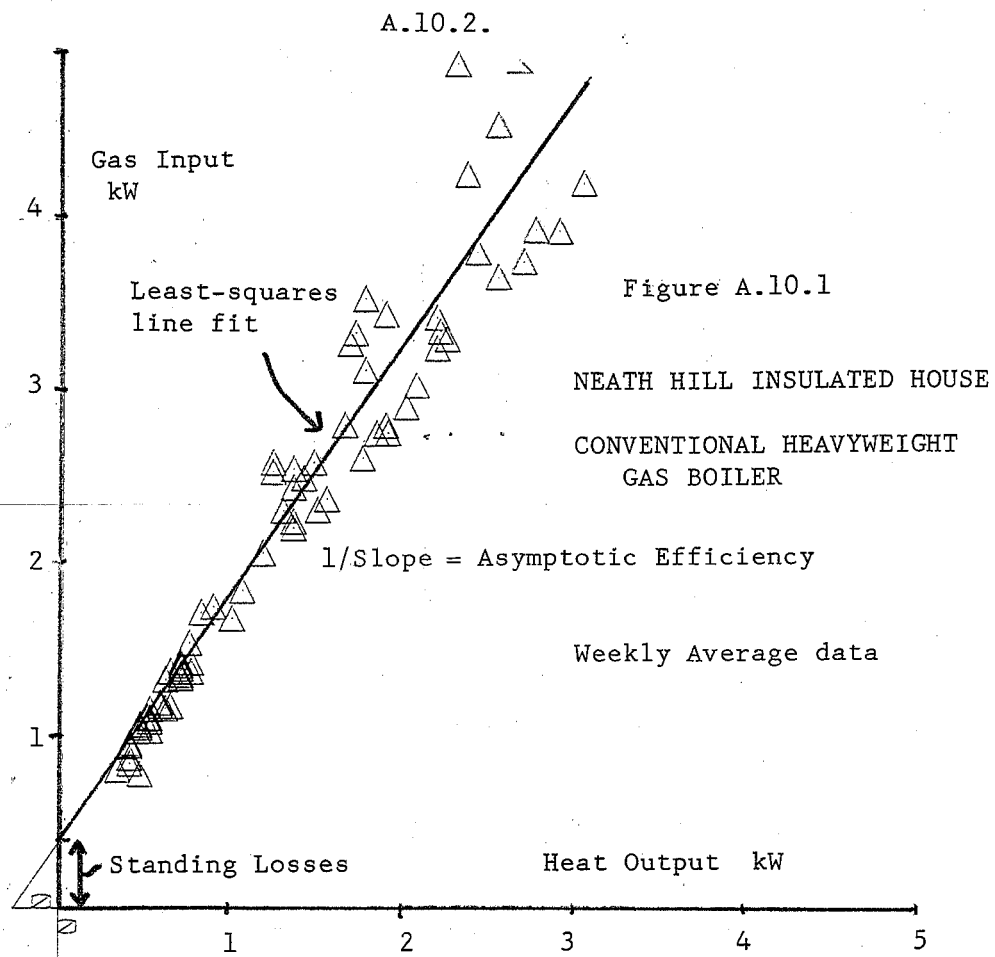
	standing losses (watts)	asymptotic efficiency
Neath Hill	355	0.80
Pennyland 2	228	0.92

These do seem to show a systematically higher standing loss and a higher slope in the Neath Hill houses. This is what we would expect from other published work comparing the efficiencies of high and low thermal capacity boilers (Pickup and Miles, 1977 and BGC, 1983).

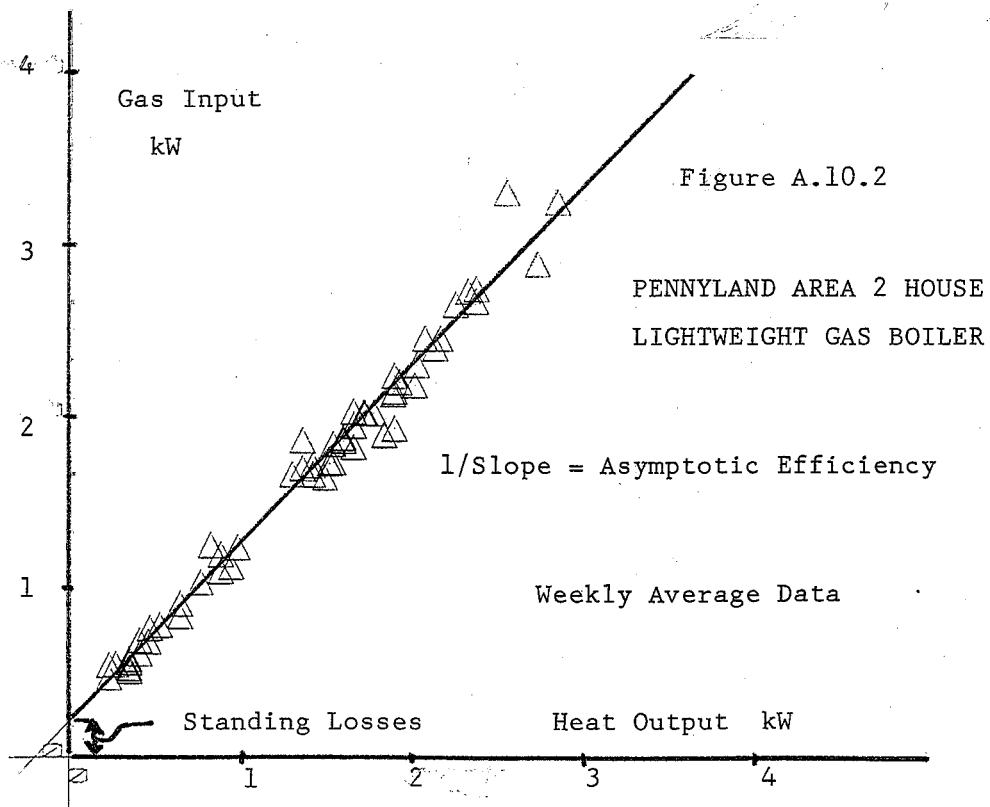
An attempt can be made to correct these figures for the calibration errors in the heat meters. The corrections cannot be done on a house by house basis except in the cases of house 15 and 63. However we can estimate the mean calibration error for the 11 heat meters which have been calibrated, and use this to correct the asymptotic efficiencies for the two estates (heat meter calibration errors do not affect the estimates of the standing losses). The mean calibration error for these heat meters is 0.92 ± 0.03 , and the resulting corrected boiler characteristics are shown below:

Mean boiler characteristics (corrected)

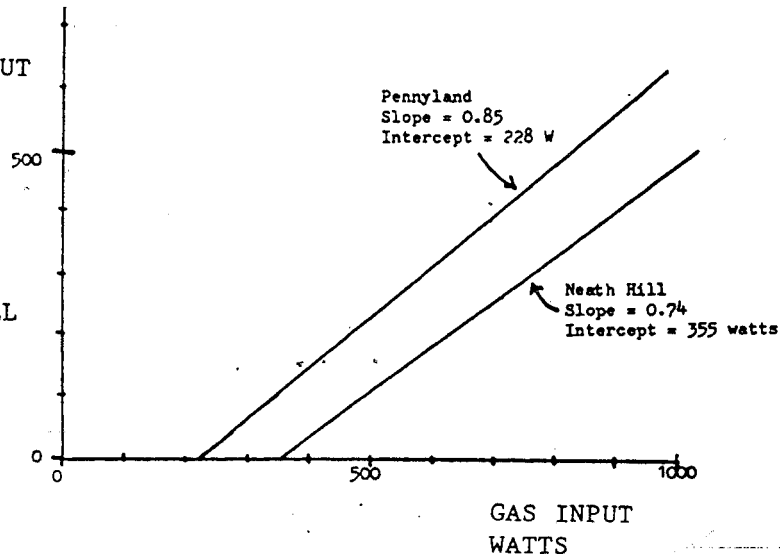
	standing losses (watts)	asymptotic efficiency
Neath Hill	355 ± 30	0.74 ± 0.01
Pennyland 2	228 ± 65	0.85 ± 0.04



Gas Input vs Boiler Heat Output: House 16



Gas Input vs Boiler Heat Output: House 76

Figure
A.10.3COMPARATIVE BOILER
EFFICIENCIES FOR
PENNYLAND AND NEATH HILL

The efficiency vs gas input curves corresponding to these characteristics are shown in figure 3. The data for Pennyland and Neath Hill, with the average efficiency/load curves superimposed are shown in figures 4 and 5.

10.2 Parameters of boiler characteristics for individual houses

The following presents the details of the regressions of the boiler input/heat output data for each house for which we have data. Points to notice are:

First that the correlation coefficients are all high (typically around 99%, though a few are lower than this). This is in line with results reported by the British Gas Corporation (BGC, 1983), and is gratifying given the rather crude nature of the measurements which were made.

Second, that the intercepts of the plots are not always very well defined, e.g. if the data near the origin are actually curved. This appears to be the case in houses 16 and 64. It must be said that accurate estimates of boiler efficiencies at very low loads is not very important, since not very much gas is used at these loads anyway.

Boiler characteristics at Neath Hill

house id	eff. standing loss (watts)	asymptotic efficiency	correlation r2
4	414	0.76	0.99
10	413	0.86	1.00
11	362	0.81	1.00
15	210	0.64	0.99
16	378	0.63	0.88

A.10.4.

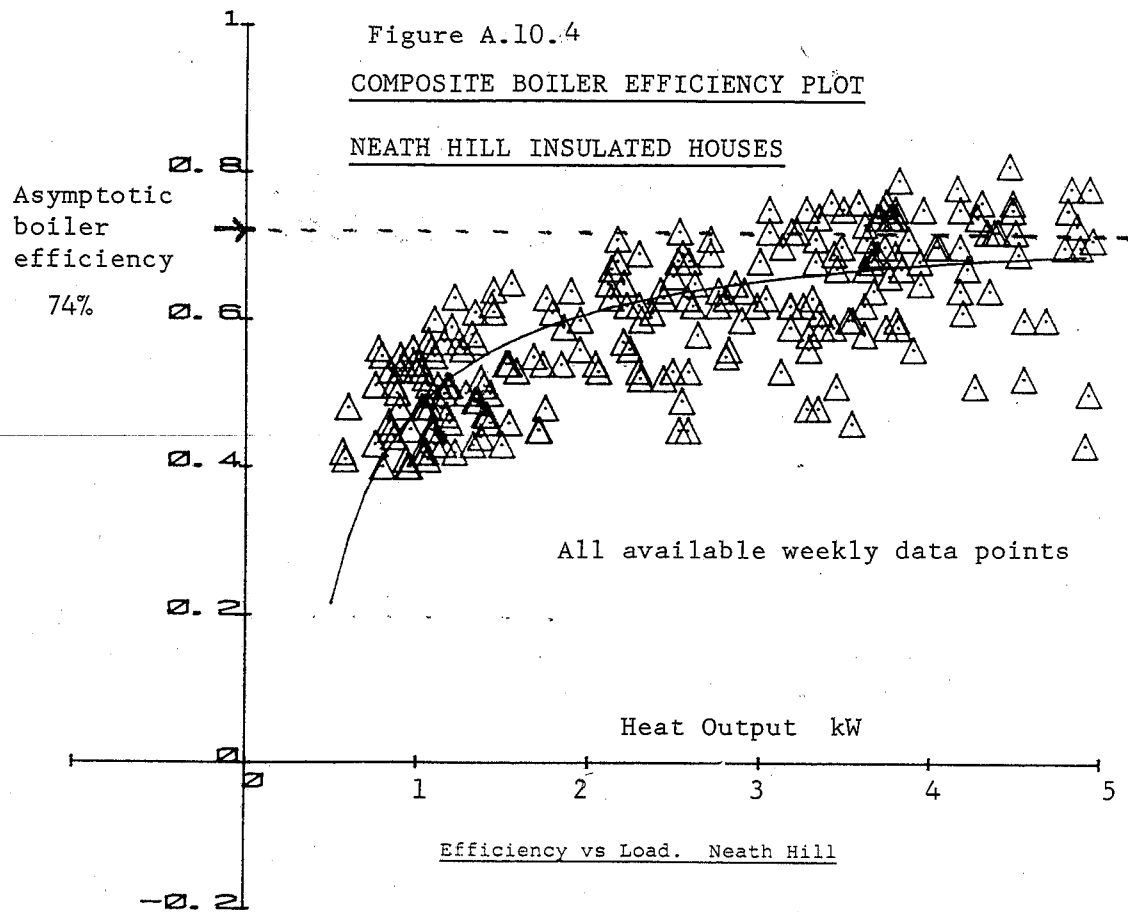
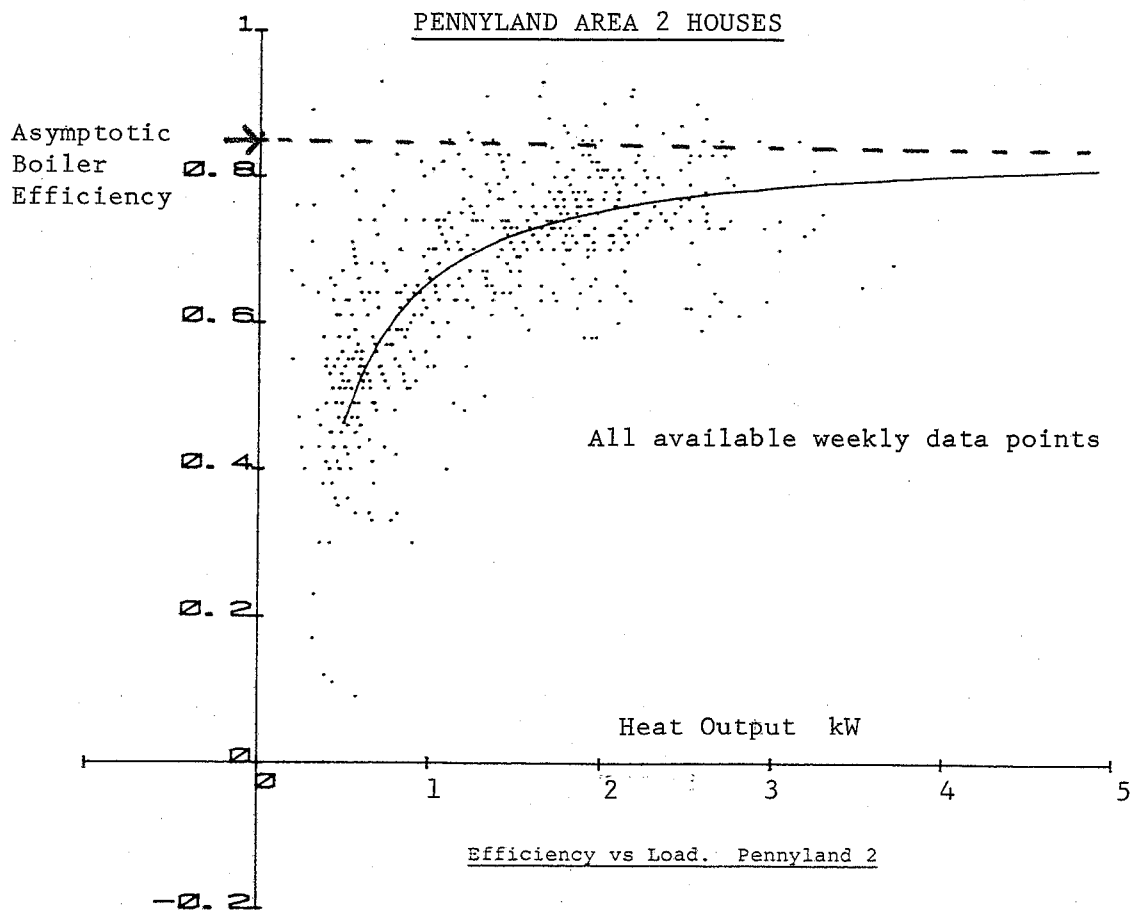


Figure A.10.5 COMPOSITE BOILER EFFICIENCY PLOT



Boiler characteristics at Pennyland 2

house id	eff. standing loss (watts)	asymptotic efficiency	correlation r2
58	237	0.94	0.98
59	156	0.78	0.99
61	198	0.89	0.99
63	320	0.90	0.98
64	311	0.88	0.98
65	321	0.89	0.99
67	196	0.81	0.98
68	162	0.83	0.98
69	260	0.88	0.96
70	189	0.71	0.98
71	307	0.91	0.98
72	252	0.83	0.96
73	242	0.84	0.88
74	192	0.83	0.96
75	100	0.81	0.99
76	206	0.84	0.98

11References

Pickup, G.A. and Miles, A.J. (1977). "The performance of wet heating systems in contemporary and future housing". IGE communication 1041, Nov 1977,

Anon (1983). "In-use efficiencies of modern domestic gas boilers". Watson House Bulletin, vol 47, no 2, 1983.

APPENDIX 11

ENERGY BALANCES

APPENDIX 11: Construction of full energy balances

The energy balances of a house or a group of houses is an attempt to fill in the values of the variables in the following equation:

$$\begin{array}{ccccccc} \text{incidental} & + & \text{solar} & + & \text{boiler} & = & \text{fabric} + \text{ventilation} + \text{DHW} + \text{flue} \\ \text{gains} & & \text{gains} & & \text{gas} & & \text{loss} & \text{loss} & & \text{loss} & \text{loss} \end{array}$$

This equation says simply that all of the energy that gets into the house has to leave it by one of four main routes. It is the task of this section to produce energy balances for 5 groups of houses, Pennyland split by insulation level and aspect, and Neath Hill. Since most of the variables have not been measured directly, they were estimated for this exercise. There are several ways in which this estimation could be done, and the answers depend on the method chosen. The two biggest uncertainties in our energy balances are the ventilation rates typical of each group of houses, and the effective solar aperture. We have used two methods, which we can label "fixed solar aperture" and "solar residual", which are described below:

'Fixed Solar Aperture' - Solar gains were calculated using measured solar radiation and solar apertures determined from regressions of weekly energy use, as described in chapter 6. The average solar apertures derived for the Neath Hill houses and the Pennyland dual aspect and single aspect houses are consistent with those calculated using the NBSLD model, adjusted in the light of thermal calibration tests on the Linford test house.

Auxiliary space heat was estimated from the boiler efficiency characteristic, and estimates of useful energy input to the DHW cylinder.

Occupancy gains were assumed to be 125 watts average.

Boiler casing losses were assumed to be 5% of boiler gas input.

Gains from DHW were assumed to be 40 watts + 10% of hot water delivered to the tap.

Gains from electricity were assumed to be 100% of electricity consumption.

For the "fixed solar aperture" energy balances, the sum of the above energy inputs was taken as the gross heat loss for each group of houses. The mean heat loss coefficient for the group was then given by the gross heat loss divided by the mean ΔT . An attempt to split gross heat loss into fabric and ventilation losses was made using estimated fabric heat loss coefficients based on the IHVE guide. The resultant ventilation losses, which contained all the residual errors from the other quantities, were unstable week by week (sometimes negative) but look plausible in most cases when averaged over each month.

The results of the "fixed solar aperture" energy balances do not provide an independent check on the solar apertures assumed. A second set of energy balances have therefore been estimated using a ventilation rate estimated from the average weekly internal/external temperature difference and the results of pressure tests carried out on a small

number of houses at Pennyland and Neath Hill. Using this method:

Fabric heat losses were estimated using IHVE guide estimates.

Infiltration was estimated from measured ΔT , and pressurisation test results, using methods discussed in appendix 7.

Gross heat loss was set equal to the sum of fabric and infiltration losses.

The solar contribution was set equal to the difference between gross heat loss and total energy input. The solar contribution therefore contains all of the residual errors in the other quantities, hence the label "residual solar".

Energy balances were constructed weekly using values of the energy consumptions and temperatures averaged over each group of houses - balances could have been constructed for each house separately and then averaged over each group, but this would have been much slower. At the weekly stage of the analysis, an adjusted gross heat loss figure was estimated for each group of houses, using the equation:

$$\text{adjusted gross heat loss} = \text{gross heat loss} * (20 - T_o) / \Delta T$$

where $T_{in} > 20^\circ\text{C}$, and

$$\text{adjusted gross heat loss} = \text{gross heat loss} \quad \text{for } T_{in} < 20^\circ\text{C}.$$

This is a fairly crude device for accounting for over-heating in summer. The difference between adjusted gross heat loss (aght) and gross heat loss (grloss) is the heat loss due to weekly average temperatures greater than 20°C , which were assumed to have no value. The gross solar contributions (grsol) for each group were reduced by this amount to give net solar contributions (nsol). This procedure is equivalent to saying that all overheating is due to the solar input to the house. Whether this assumption makes sense will depend on the comparisons that one is trying to make.

The weekly energy balances were then converted to monthly balances which are presented below. The monthly figures are in the units of mean watts (or watts/m²), while the annual averages are shown in units of mean watts and kWh/a.

sol	=	solar radiation W/m ²
dt	=	ΔT K
ta	=	ambient air temperature $^\circ\text{C}$
v	=	ventilation rate ACH
grloss	=	gross heat requirement W
sp	=	auxiliary space heat W
el	=	electricity consumption W
grfh	=	gross free heat, metabolic gains+el+DHW+boiler casing losses
grsol	=	gross solar contribution W
aght	=	adjusted gross heat loss (T_{in} restricted to 20°C) W
nsol	=	net solar contribution to adjusted gross heat loss W

A.11.3.

First we present the "fixed solar aperture" energy balances:

Pennyland 1 dual aspect.

month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	107.6	5.6	14.8	0.07	977	38	282	509	431	907	360
10 :	75.4	8.7	10.3	-0.14	1418	546	307	570	301	1418	302
11 :	65.2	10.0	8.0	0.15	1817	910	356	647	261	1817	260
12 :	49.4	14.7	0.8	0.17	2689	1774	372	718	197	2689	198
1 :	49.3	14.2	1.9	0.29	2712	1777	390	738	197	2712	197
2 :	42.4	11.8	5.0	0.28	2238	1393	353	676	170	2238	170
3 :	97.7	11.3	5.9	0.53	2374	1310	359	673	391	2374	391
4 :	117.6	8.9	8.6	0.38	1781	731	305	579	470	1773	463
5 :	109.6	7.2	11.9	0.23	1347	381	280	528	439	1324	415
6 :	106.3	5.1	15.9	0.33	963	39	276	499	425	722	185
7 :	100.6	4.7	16.7	0.35	926	18	285	505	402	630	107
8 :	100.2	4.0	17.4	0.82	894	0	274	493	401	494	2
an :	85.2	8.9	9.7	0.30	1694	756	321	597	341	1608	255
an :	746.8	8.9	9.7	0.30	14840	6627	2814	5226	2987	14085	2232

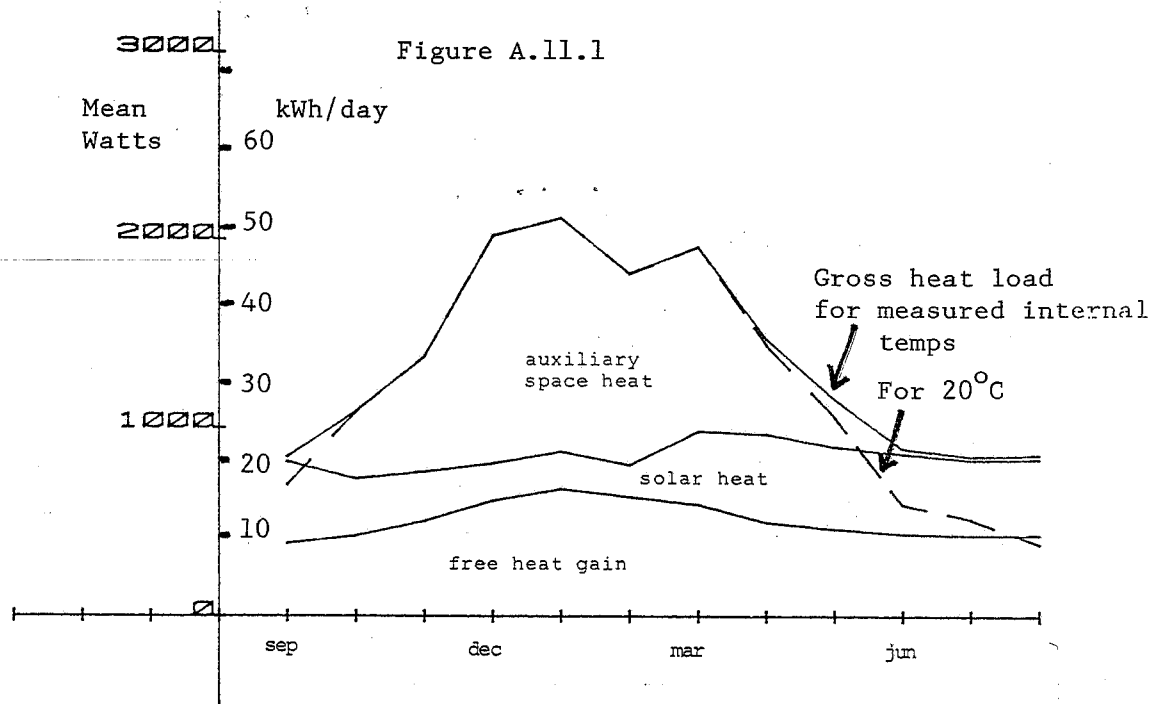
Pennyland 1 single aspect.

month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	107.6	6.6	14.8	0.00	1170	14	287	511	646	943	419
10 :	75.4	9.9	10.3	-0.31	1561	531	314	577	452	1497	388
11 :	65.2	11.3	8.0	-0.16	1905	862	363	651	391	1871	357
12 :	49.4	16.0	0.8	-0.23	2615	1562	423	756	296	2615	296
1 :	49.3	15.7	1.9	-0.12	2692	1633	423	763	296	2692	296
2 :	42.8	13.0	5.0	-0.10	2245	1275	396	713	257	2245	257
3 :	97.7	12.7	5.9	0.26	2523	1245	381	692	586	2523	586
4 :	117.6	10.8	8.6	0.06	1987	684	326	598	706	1928	647
5 :	109.6	8.4	11.9	0.21	1636	438	290	541	658	1469	491
6 :	106.3	5.5	15.9	0.41	1151	21	271	492	638	783	270
7 :	100.6	5.1	16.7	0.48	1096	9	266	484	604	690	198
8 :	100.2	4.4	17.4	0.98	1103	0	285	502	601	567	65
an :	85.3	10.0	9.7	0.12	1822	701	336	609	512	1652	342
an :	747.0	10.0	9.7	0.12	15961	6143	2948	5332	4485	14472	2296

Pennyland 2 dual aspect.

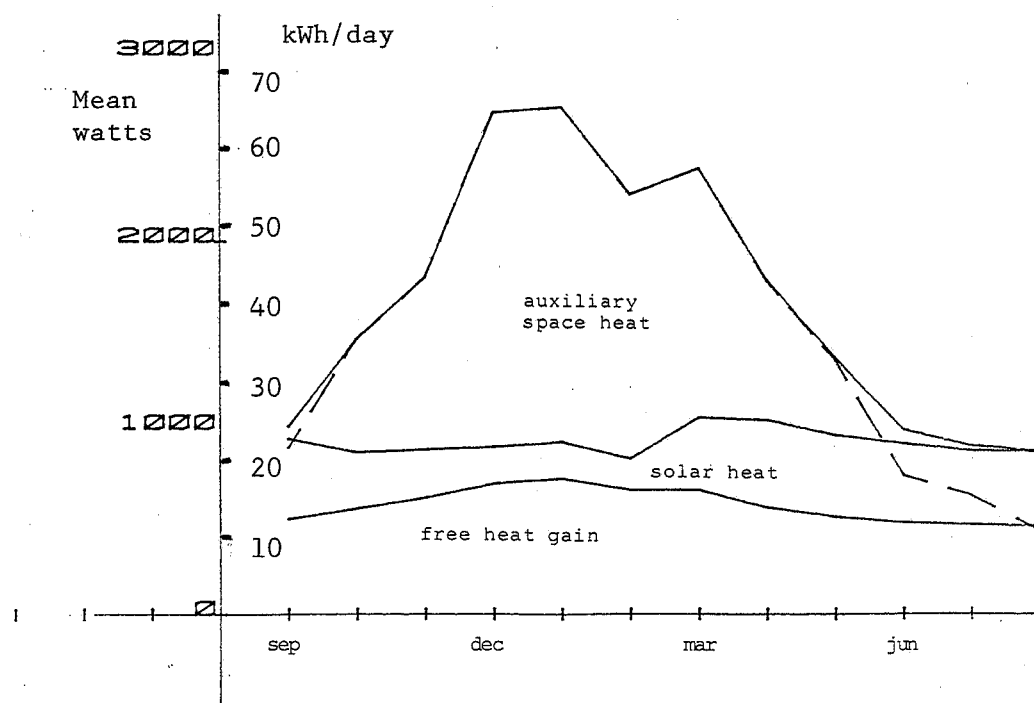
month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	107.6	6.3	14.8	0.44	862	25	186	407	431	719	288
10 :	75.4	9.3	10.3	0.14	1109	371	189	437	301	1085	277
11 :	65.2	10.7	8.0	0.32	1397	615	253	522	261	1397	260
12 :	49.4	15.5	0.8	0.37	2088	1272	308	619	197	2088	198
1 :	49.3	15.4	1.9	0.44	2129	1294	325	638	197	2129	197
2 :	42.4	12.6	5.0	0.52	1822	1054	301	599	170	1822	169
3 :	97.7	12.6	5.9	0.69	1971	1004	285	576	391	1971	391
4 :	117.6	10.3	8.6	0.47	1464	483	255	510	470	1426	432
5 :	109.6	8.3	11.9	0.46	1151	231	246	481	439	1039	327
6 :	106.3	5.8	15.9	0.67	885	6	237	454	425	571	111
7 :	100.6	5.4	16.7	0.69	846	0	230	444	402	503	59
8 :	100.2	5.3	17.4	0.82	850	4	229	445	401	369	-80
an :	85.2	9.9	9.7	0.51	1393	539	256	514	341	1273	220
an :	746.8	9.9	9.7	0.51	12205	4717	2241	4501	2987	11149	1931

Energy balance for Pennyland 2 dual aspect



Energy balance for Pennyland 1 dual aspect

Figure A.11.2



Pennyland 2 single aspect.

month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	107.6	7.6	14.8	0.45	1189	23	316	521	646	829	286
10 :	75.9	11.0	10.4	0.19	1518	478	345	585	452	1327	261
11 :	65.2	11.9	8.0	0.33	1759	748	361	620	391	1694	326
12 :	49.4	17.4	0.8	0.26	2478	1487	390	695	296	2478	296
1 :	49.3	16.9	1.9	0.24	2378	1393	397	698	296	2387	296
2 :	42.4	14.1	5.0	0.29	2045	1121	386	670	257	2045	257
3 :	97.7	14.2	5.9	0.48	2254	989	406	679	586	2230	562
4 :	117.6	11.8	8.6	0.41	1815	514	354	595	706	1701	592
5 :	109.6	9.8	11.9	0.41	1505	280	343	567	658	1214	367
6 :	106.3	6.5	15.9	0.81	1184	12	331	534	638	6684	138
7 :	100.6	6.2	16.7	0.85	1150	0	346	547	604	594	48
8 :	100.2	6.2	17.4	1.00	1215	2	409	612	601	431	-183
an :	85.3	11.2	9.7	0.48	1718	596	365	611	512	1468	262
an :	747.1	11.2	9.7	0.48	15050	5218	3200	5350	4485	12860	2295

Neath Hill.

month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	113.0	5.7	14.8	0.30	1050	57	287	541	452	956	358
10 :	79.3	9.3	11.4	0.28	1735	766	338	651	317	1583	166
11 :	65.2	11.6	8.0	0.52	2346	1321	406	765	261	2297	211
12 :	49.4	17.1	0.8	0.41	3317	2251	442	869	197	3317	198
1 :	49.8	16.6	1.7	0.47	3276	2207	444	870	199	3276	199
2 :	42.4	14.1	5.0	0.45	2775	1798	411	808	170	2775	170
3 :	97.7	13.3	5.9	0.76	2919	1725	418	804	391	2919	391
4 :	117.6	10.6	8.6	0.38	2058	934	330	654	470	1969	382
5 :	109.6	8.3	11.9	0.23	1515	480	311	597	439	1372	296
6 :	106.3	5.6	15.9	0.33	1036	65	297	546	425	690	79
7 :	100.6	5.1	16.7	0.25	925	13	265	510	402	591	69
8 :	100.2	4.8	17.4	0.53	955	14	298	541	401	477	-77
an :	85.3	10.3	9.6	0.41	2025	1000	356	685	341	1886	202
an :	747.2	10.3	9.6	0.41	17742	8757	3121	5996	2989	16519	1766

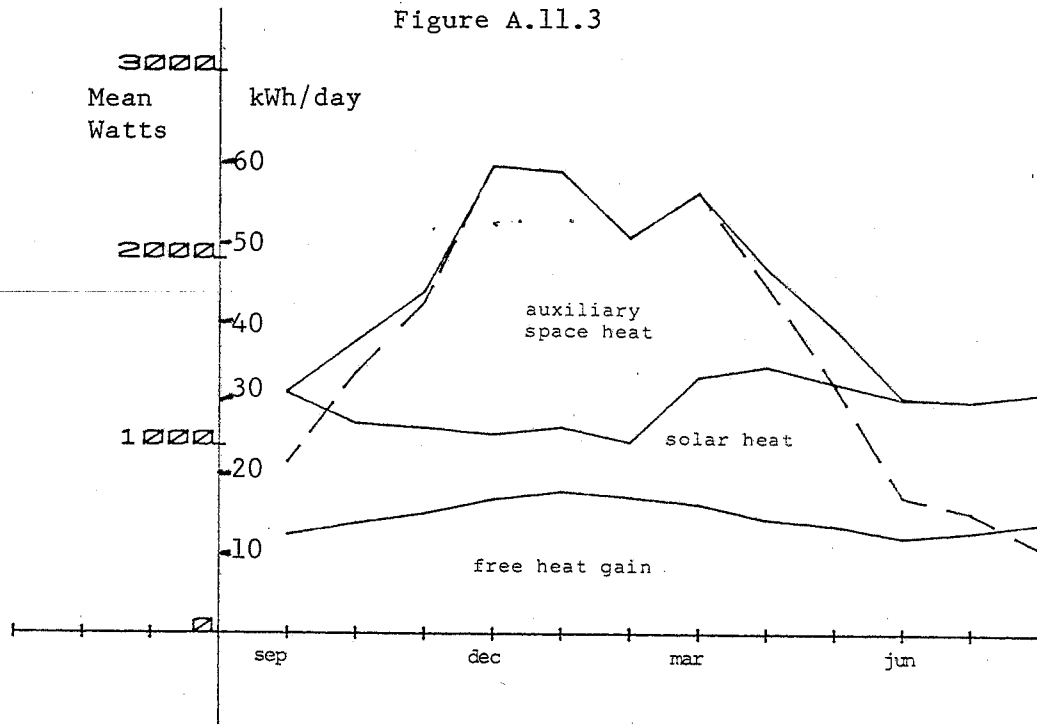
Next we present the "residual solar" energy balances:

Pennyland 1 dual aspect.

month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	107.6	5.6	14.8	0.40	1115	38	282	509	568	1029	482
10 :	75.4	8.7	10.3	0.27	1660	546	307	570	544	1660	544
11 :	65.2	10.0	8.0	0.28	1915	910	356	647	359	1915	358
12 :	49.4	14.7	0.8	0.30	2846	1774	372	718	355	2846	354
1 :	49.3	14.2	1.9	0.30	2741	1777	390	738	226	2741	226
2 :	42.4	11.8	5.0	0.29	2263	1393	353	676	195	2263	194
3 :	97.7	11.3	5.9	0.28	2176	1310	359	673	192	2176	193
4 :	117.6	8.9	8.6	0.27	1711	731	305	579	400	1704	394
5 :	109.6	7.2	11.9	0.40	1446	381	280	528	537	1421	512
6 :	106.3	5.1	15.9	0.40	1017	39	276	499	479	816	278
7 :	100.6	4.7	16.7	0.40	949	18	285	505	426	663	140
8 :	100.2	4.0	17.4	0.40	793	0	274	493	300	467	-25
an :	85.2	8.9	9.7	0.33	1730	756	321	597	377	1653	300
an :	746.8	8.9	9.7	0.33	15158	6627	2814	5226	3305	14483	2630

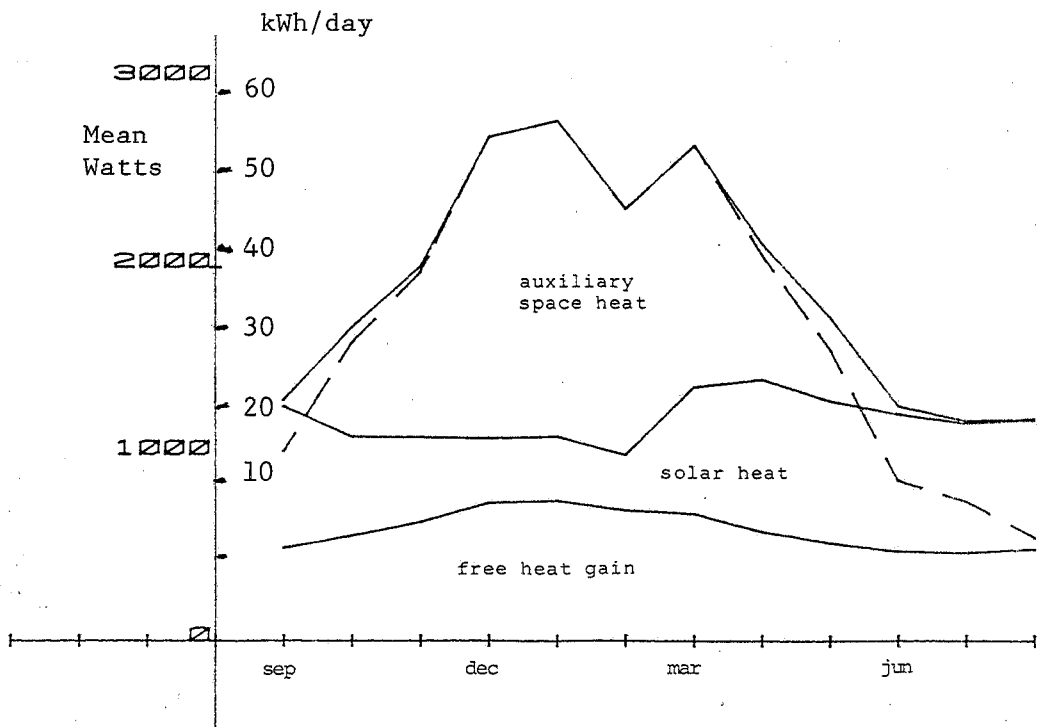
Energy balance for Pennyland 2 single aspect

Figure A.11.3



Energy balance for Pennyland 1 single aspect

Figure A.11.4.



A.11.7.

Pennyland 1 single aspect.

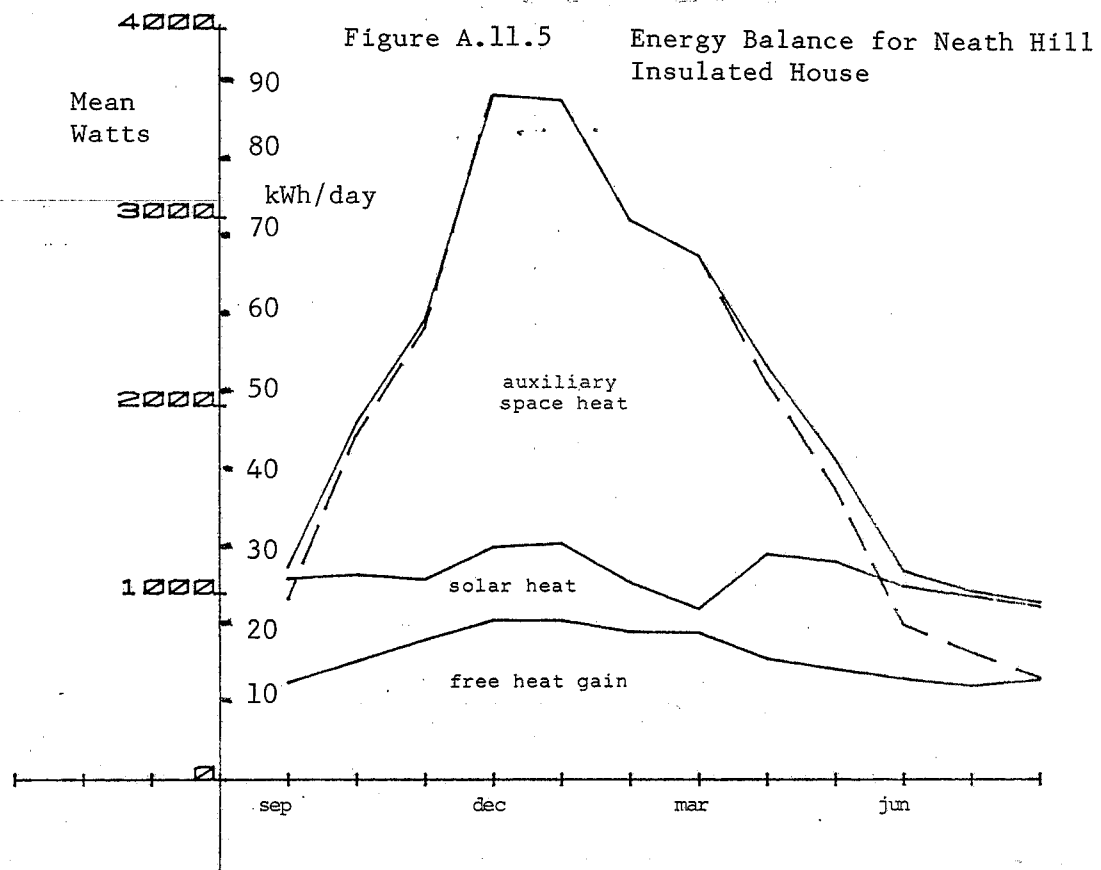
month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	107.6	6.6	14.8	0.40	1368	14	287	511	843	1086	561
10 :	75.4	9.9	10.3	0.28	1980	531	314	577	872	1900	792
11 :	65.2	11.3	8.0	0.28	2270	862	363	651	756	2230	716
12 :	49.4	16.0	0.8	0.31	3239	1562	423	756	921	3239	921
1 :	49.3	15.7	1.9	0.31	3182	1633	423	763	787	3182	787
2 :	42.8	13.0	5.0	0.29	2608	1275	396	713	620	2608	620
3 :	97.7	12.7	5.9	0.29	2549	1245	381	692	613	2549	613
4 :	117.6	10.8	8.6	0.28	2160	684	326	598	878	2098	816
5 :	109.6	8.4	11.9	0.40	1749	438	290	541	771	1571	593
6 :	106.3	5.5	15.9	0.40	1150	21	271	492	636	848	335
7 :	100.6	5.1	16.7	0.40	1060	9	266	484	567	689	196
8 :	100.2	4.4	17.4	0.40	919	0	285	502	417	506	4
an :	85.3	10.0	9.7	0.34	2034	701	336	609	724	1892	582
an :	747.0	10.0	9.7	0.34	17814	6143	2948	5332	6339	16573	5098

Pennyland 2 dual aspect.

month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	107.6	6.3	14.8	0.40	862	25	186	407	431	704	273
10 :	75.4	9.3	10.3	0.24	1159	371	189	437	351	1134	326
11 :	65.2	10.7	8.0	0.24	1342	615	253	522	205	1342	205
12 :	49.4	15.5	0.8	0.27	1976	1272	308	619	86	1976	86
1 :	49.3	15.4	1.9	0.27	1958	1294	325	638	26	1958	26
2 :	42.4	12.6	5.0	0.26	1596	1054	301	599	-56	1596	-57
3 :	97.7	12.6	5.9	0.25	1584	1004	285	576	4	1584	4
4 :	117.6	10.3	8.6	0.24	1298	483	255	510	305	1266	272
5 :	109.6	8.3	11.9	0.40	1129	231	246	481	417	1019	307
6 :	106.3	5.8	15.9	0.40	797	6	237	454	337	556	96
7 :	100.6	5.4	16.7	0.40	739	0	230	444	296	451	8
8 :	100.2	5.3	17.4	0.40	718	4	229	445	270	359	-90
an :	85.2	9.9	9.7	0.31	1272	539	256	514	220	1172	120
an :	746.8	9.9	9.7	0.31	11141	4717	2241	4501	1924	10266	1047

Pennyland 2 single aspect.

month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	107.6	7.6	14.8	0.40	1154	23	316	521	610	795	251
10 :	75.9	11.0	10.4	0.25	1555	478	345	585	492	1361	298
11 :	65.2	11.9	8.0	0.25	1698	748	361	620	330	1635	268
12 :	49.4	17.4	0.8	0.28	2505	1487	390	695	324	2505	324
1 :	49.3	16.9	1.9	0.28	2431	1393	397	698	340	2428	337
2 :	42.4	14.1	5.0	0.26	2014	1121	386	670	224	2014	224
3 :	97.7	14.2	5.9	0.26	2023	989	406	679	355	2002	333
4 :	117.6	11.8	8.6	0.25	1673	514	354	595	563	1571	462
5 :	109.6	9.8	11.9	0.40	1490	280	343	567	643	1207	361
6 :	106.3	6.5	15.9	0.40	996	12	331	534	451	621	75
7 :	100.6	6.2	16.7	0.40	947	0	346	547	401	504	-43
8 :	100.2	6.2	17.4	0.40	943	2	409	612	330	401	-212
an :	85.3	11.2	9.7	0.32	1627	596	365	611	420	1433	227
an :	747.1	11.2	9.7	0.32	14250	5218	3200	5350	3683	12552	1985



A.11.9.

Neath Hill.

month:	sol	dt	ta	v	grloss	sp	el	grfh	grsol	aght	nsol
9 :	113.0	5.7	14.8	0.58	1170	57	287	541	573	1060	462
10 :	79.3	9.3	11.4	0.61	1949	766	338	651	532	1782	365
11 :	65.2	11.6	8.0	0.64	2453	1321	406	765	368	2403	317
12 :	49.4	17.1	0.8	0.71	3706	2251	442	869	587	3706	586
1 :	49.8	16.6	1.7	0.70	3580	2207	444	870	502	3580	503
2 :	42.4	14.1	5.0	0.67	3016	1798	411	808	410	3016	410
3 :	97.7	13.3	5.9	0.66	2822	1725	418	804	294	2822	293
4 :	117.6	10.6	8.6	0.63	2239	934	330	654	652	2149	561
5 :	109.6	8.3	11.9	0.61	1734	480	311	597	658	1567	491
6 :	106.3	5.6	15.9	0.57	1156	65	297	546	546	839	228
7 :	100.6	5.1	16.7	0.57	1046	13	265	510	523	680	158
8 :	100.2	4.8	17.4	0.57	984	14	298	541	430	542	-12
an :	85.3	10.3	9.6	0.63	2190	1000	356	685	506	2049	365
an :	747.2	10.3	9.6	0.63	19182	8757	3121	5996	4430	17947	3194

Comments on energy balances

The annual energy balances for all the groups of houses look reasonable. However a detailed examination of the balances suggests a number of points.

The fixed solar aperture energy balance for the Pennyland 1 single aspect houses implies negative ventilation rates in the months of October to February. This is obviously quite unrealistic. Possible explanations can be sought in a number of places. The gross heat loss of these houses may have been underestimated, due perhaps to underestimation of the solar contribution or the auxiliary space heat output. Since the solar contribution to these houses is already large, the former seems at first sight plausible. However the largest discrepancies occur when the solar contribution is smallest, and would imply errors of the order of 100% in this variable. In fact, it seems unlikely that the solar aperture of these houses has been underestimated - 7m^2 is already close to the theoretical upper limit of about 8m^2 (taking into account glazed south facing area and transmissivity of single glass). Regarding the auxiliary heat output, it is unlikely that the total useful heat output of the boilers at Pennyland is underestimated by the procedures used for this exercise. It is however possible that the useful heat input to the DHW cylinder has been overestimated, perhaps to 50 mean watts, and this would result in an underestimation of the auxiliary space heat output by nearly the same amount.

Turning to the other side of the equation, there are three main possible explanations for the apparently low ventilation rate in the Pennyland 1 single aspect houses. The first is that the fabric heat loss coefficients have been overestimated by between 10 and 15%. There is no way that this can be checked with the data currently to hand, since no in-situ measurements of U values have been made at Pennyland or Neath Hill. This cannot therefore be ruled out, though it is not clear why it should affect the single aspect houses at Pennyland so much more than the dual aspect houses. The second possible explanation is that some of the occupants of these houses have made modifications to their houses which reduce some of the components of fabric heat loss. The obvious thing to look for is DIY double glazing. If 10% of windows were double glazed the fabric heat loss coefficient of the houses would be reduced by about 5 W/K. At least one of these houses (house 25) is known to have had DIY double glazing installed. The third possible explanation is that internal temperatures in these houses have been overestimated. It is noteworthy that about one half of the dual aspect houses at Pennyland had their external temperature probes mounted on the south side of the house, while all of the probes in the single aspect houses were mounted on the north side of the house. This would tend to lead to ΔT 's and internal temperature being underestimated in the dual aspect houses and overestimated in the single aspect houses, particularly in summer. A one degree error in midwinter would account for about 10 W/K, which is about a third of the discrepancy. The above comments on the Pennyland 1 single aspect houses have been referred to the fixed solar aperture energy balance. The residual solar balance for this group of houses shows a corresponding peculiarity - a very high effective solar aperture for the winter months (a massive 19m^2 in December). This emphasises the fact that the discrepancy in this group of houses cannot be assigned wholly to solar.

Turning now to the other groups of houses, the fixed solar aperture

energy balance for the Pennyland 2 single aspect houses suggests that there may be a spring cleaning effect in these houses, with ventilation rates rising sharply at the ends of the heating season.

A comparison of the two energy balances for Neath Hill is interesting. Although the method used to estimate ventilation rates for the residual solar energy balances is crude, it is unlikely to give an underestimate. The fact that the ventilation rates in the fixed solar aperture energy balance are consistently lower than the ones in the residual solar balance suggests that the former are too low. This may mean (among other things) that the effective solar aperture of 4m^2 assumed in the fixed solar energy balance for Neath Hill was too high.

The residual solar energy balances for the Pennyland houses are interesting in their own right since they may provide us with independent estimates of the solar contributions to these houses. The effective annual average solar apertures derived from these energy balances are sensitive to the assumption made about summer ventilation rates. These cannot sensibly be estimated in the same way as the winter ventilation rates, because of far greater window opening in the warmer months. We have therefore simply set the ventilation rate to 0.4 ACH for the period May to September, following the convention used in the analysis of the Great Linford data. For what they are worth the effective solar apertures estimated on this basis are:

Solar apertures from energy balances:		
	single	dual
Pennyland 1	8.5	4.4
Pennyland 2	4.9	2.6

The difference between the Pennyland 1 and 2 houses is not expected but is probably not significant given the uncertainties involved in constructing the energy balances. The figures are consistent with the results of the regression analysis presented in appendix 9 and provide some support for the proposition that the single aspect houses at Pennyland are more solar than the dual aspect houses.

The most valuable function of the energy balances presented above is to show the relative importance of free heat gains, solar energy, and auxiliary space heat for meeting the gross heat requirements of the different groups of houses.

These contributions to the adjusted gross heat requirement of the five groups of houses are shown in the pie charts and Sankey diagrams below. It should be stressed that these are derived from measured data, incorporating both the differences in house performance and differences due to occupant behaviour and this should be borne in mind when making comparisons.

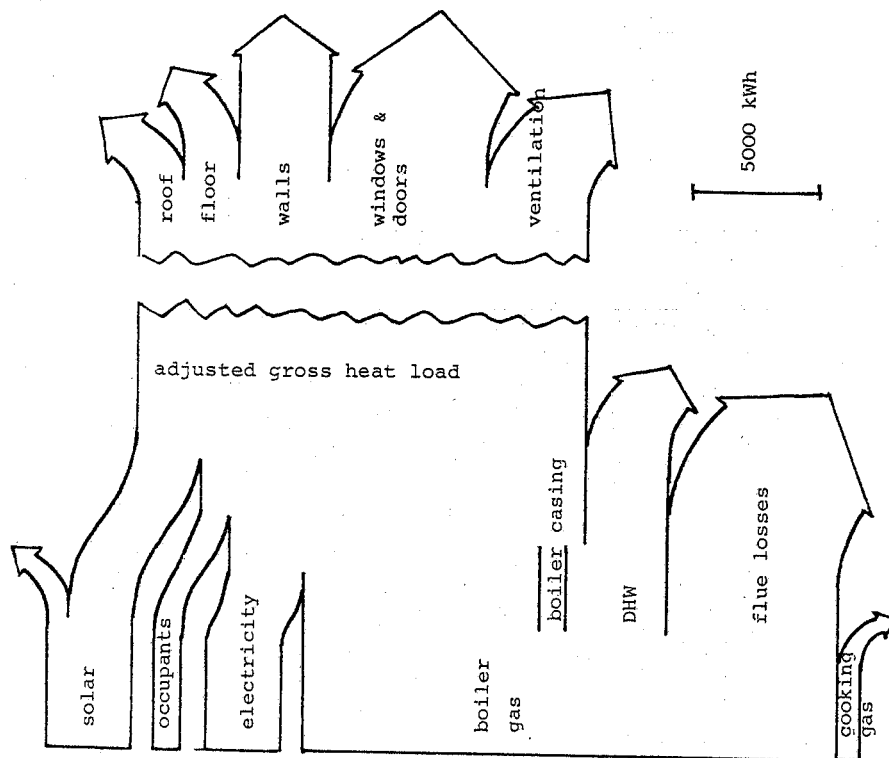


Figure A.11.6. Sankey Diagram for Neath Hill Insulated House

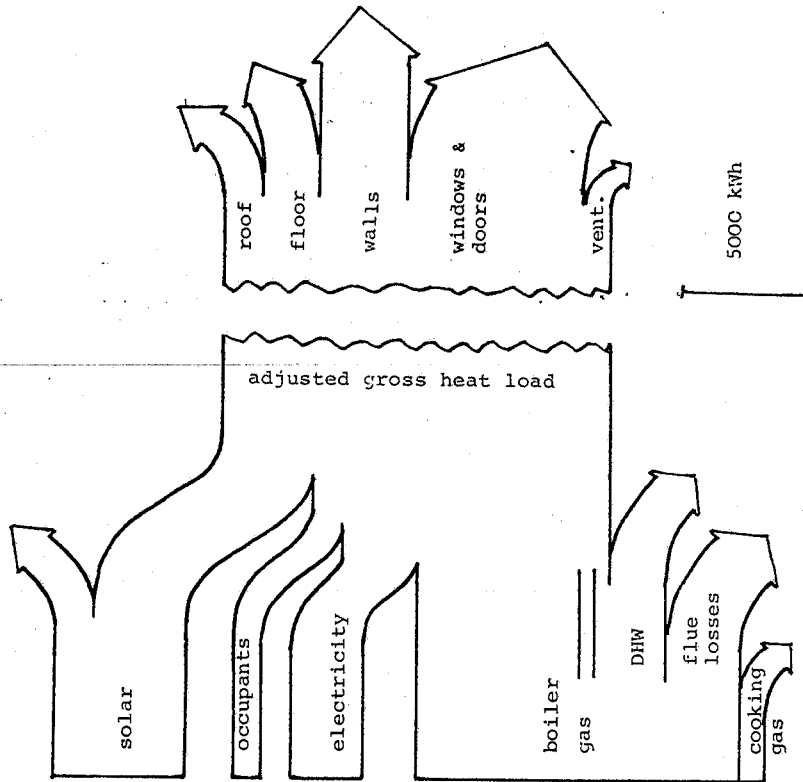


Figure A.11.8

Sankey diagram for Pennyland 1 single aspect.

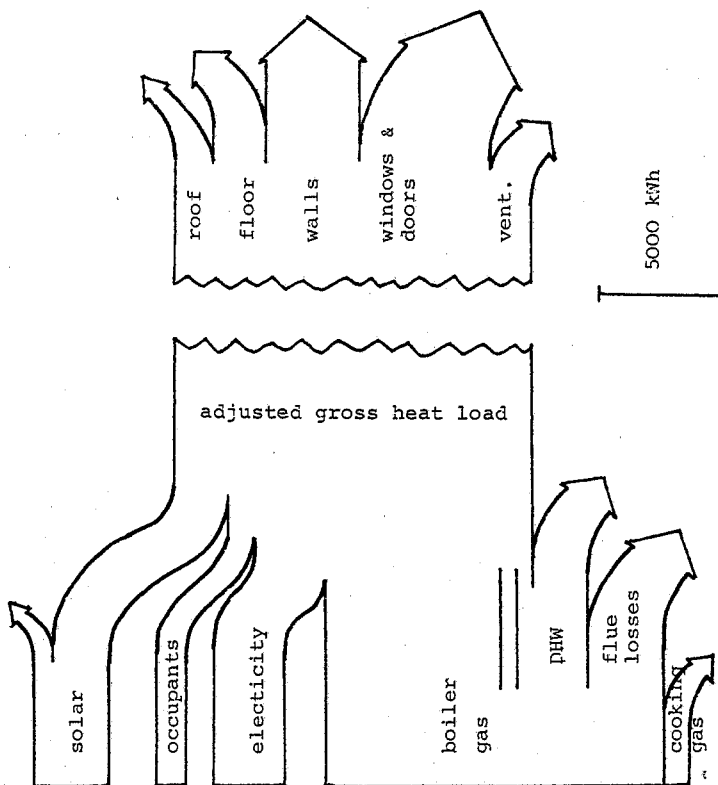


Figure A.11.7:

Sankey diagram for Pennyland 1 dual aspect.

A.11.14

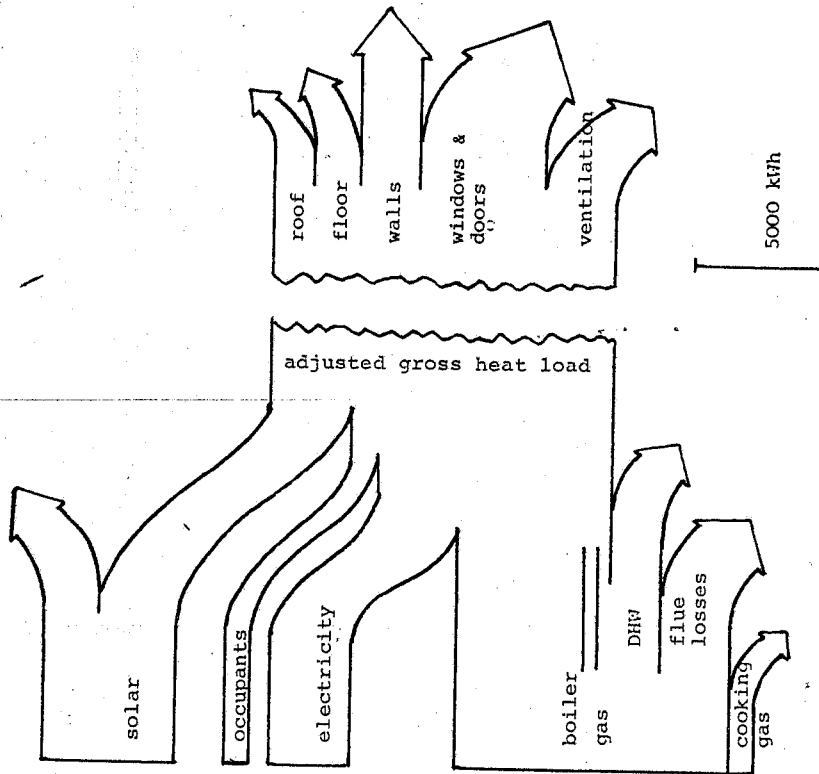


Figure A.11.10

Sankey diagram for Pennyland 2 single aspect.

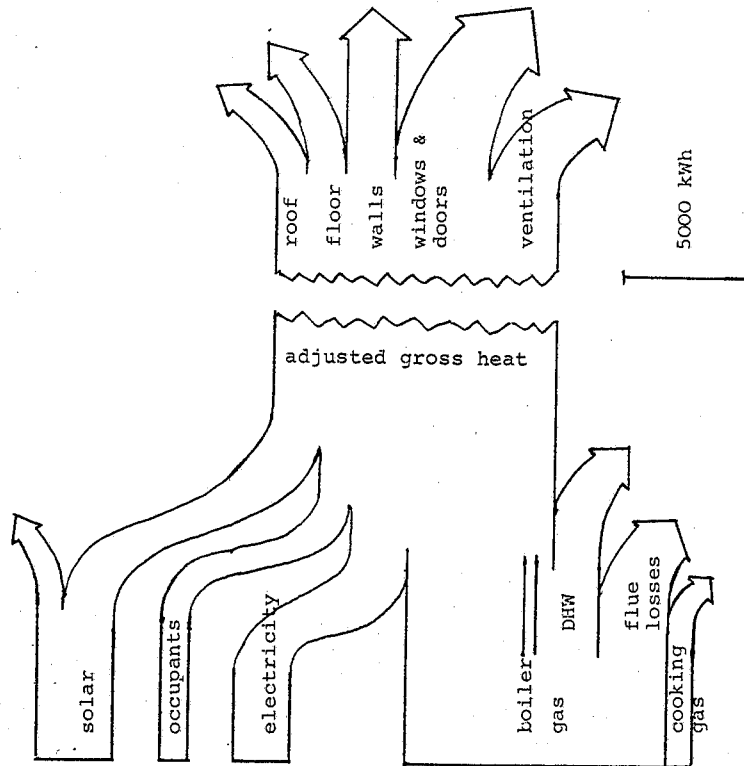
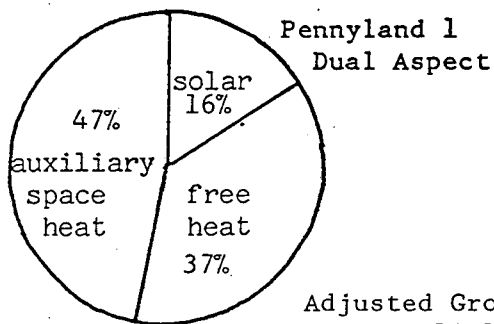
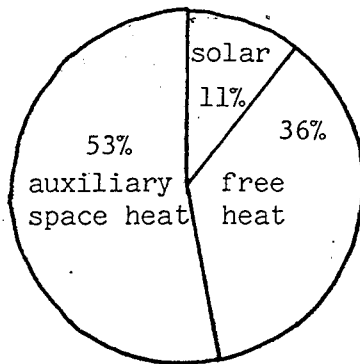
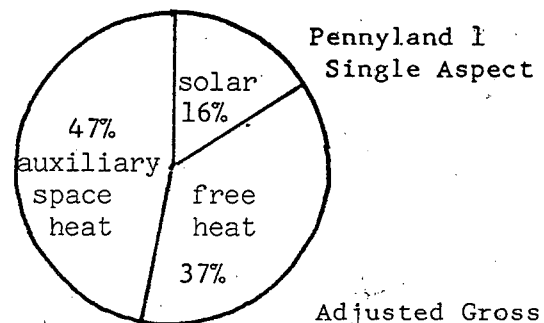
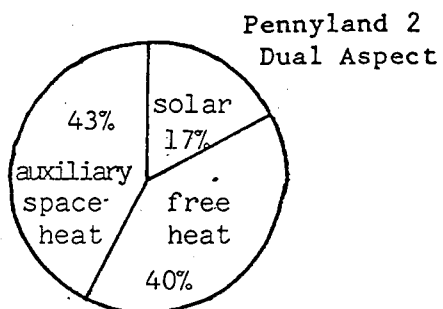
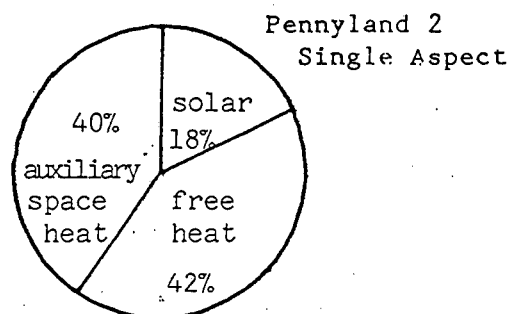


Figure A.11.9.

Sankey diagram for Pennyland 2 dual aspect.

Figure A.11.11

Annual Energy Contributions to Adjusted
Gross Heat LossFIXED SOLAR APERTURESSolar gains calculated
from regressionsNeath Hill Insulated
HouseAdjusted Gross Heat
Loss 16,500 kWh/yrAdjusted Gross
Heat Loss 14,100 kWh/yrAdjusted Gross
Heat Loss 14,500 kWh/yrAdjusted Gross Heat
Loss 11,100 kWh/yrAdjusted Gross Heat
Loss 12,900 kWh/yr